STELLAR ABSOLUTE FLUXES AND ENERGY DISTRIBUTIONS FROM 0.32 to 4.0 µm

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ABSTRACT. The absolute fluxes and energy distributions of stars are the foundation of the calibration of fundamental effective temperatures and bolometric corrections. In this paper I will review recent progress in the calibration of absolute fluxes and energy distributions in the visual and IR parts of the spectrum. In the visual, the calibration of the absolute flux and energy distribution of Vega has settled down well, and the remaining difficulties include the lack of a worldwide common list of brighter secondary standard stars, the lack of enough satisfactory fainter secondary standard stars and the possibility of variability in Vega. In the IR, the process of arriving at a dependable and accurate calibration, and of linking it to commonly used photometric systems, is in its infancy. A final, and rather special problem, is the question of the calibration of the Sun. The Sun is a special case both because it is so well studied astrophysically and because its extreme brightness makes it very difficult to calibrate photometrically. Some progress has recently been made on the calibration of the absolute flux and energy distribution of the Sun, and I will discuss this work.

1. INTRODUCTION

I am concerned here with the measurement of the absolute flux and energy distribution of the stars within that part of the spectrum which includes thermal radiation from the apparent surface of the star. In terms of the calibration of fundamental stellar quantities, the <u>apparent total flux</u>, f, radiated by a star, is related to the effective temperature, T_{eff}, and angular diameter, $\theta = (2R/d)$, of the star, through the equation:

$$f = (\theta^2/4)\sigma T^4_{eff}. \quad (1)$$

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The apparent bolometric magnitude, m_{bol}, is related to the apparent total flux through the equation:

$$m_{bol} = -2.5 \log_{10} f + C = V + B.C., \tag{2}$$

where V is the apparent visual magnitude in the Johnson UBV system, B.C. is the bolometric correction, and the zero point constant, C, is determined by reference to the Sun:

$$m_{bol,*} - m_{bol,o} = -2.5 \log_{10}(f_*/f_o). \tag{3}$$

The measured quantities in these equations are the apparent total fluxes, the angular diameters, and the V magnitudes of the Sun and stars. The measurement of the V magnitudes of the stars is not a major contributor to the errors here, so I will not discuss it further. The V magnitude of the Sun is discussed below, and the measurement of angular diameters is discussed by Hanbury Brown (1985) and Davis (1985) in this symposium.

The quantity which I have been calling the "apparent total flux" is the integral over wavelength (or frequency) of the apparent monochromatic flux, f_λ (or f_ν). In fact, we do not measure the apparent total flux because of the nature of our detectors and the transmission of the Earth's atmosphere, and what is actually done is to measure the apparent monochromatic flux at a number of wavelengths and to perform the integral numerically. The measurement of the apparent monochromatic flux of a star divides naturally into three wavelength ranges: a) the UV, with wavelengths shortward of the atmospheric cutoff at about 0.32 μm; these measurements must be made from above the atmosphere, b) the "visual," with wavelengths between the atmospheric cutoff and about 1.0 μm, and c) the IR, with wavelengths longer than 1.0 μm. The UV is discussed by A. D. Code (1985) in this symposium.

I will further separate the measurement of the apparent monochromatic flux into two parts: the measurement of the absolute monochromatic flux, which is measured at some standard wavelength, such as 5000 or 5556A, and the measurement of the absolute energy distribution, which is the apparent monochromatic flux normalized to the standard wavelength. I emphasize the term "absolute" to distinguish it from conventional relative photometry, in which the measurement of the program stars is referred to one or more standard stars. We make measurements of the absolute monochromatic flux and energy distribution for only a limited number of stars, which become the standard stars. For traditional and practical reasons the star Vega (Alpha Lyrae = HR 7001 = HD 172167) is the primary standard star. A number of other bright early-type stars have been defined as secondary standard stars; the fluxes and energy distributions of these stars have, for the most part, been determined through careful measurements relative to Vega. In some cases the secondary standards have been measured absolutely. For the sake of brevity, I will hereafter refer to the absolute monochromatic flux and absolute energy distribution as the "flux" and "energy distribution" of the star. There will be no confusion since there is no longer any reason to consider the total flux, and since the term "absolute" is to be understood during the entire discussion. That is, I will specifically refer to the relative flux (or energy distribution), if that is what I mean.

In addition to their being the basis of the determination of fundamental effective temperatures and bolometric corrections, absolute fluxes and energy distributions are very important because of what can be learned by fitting the calculated energy distributions and fluxes from model atmospheres to the observations. Firstly, the degree of fit can be used to diagnose problems with the models and to improve the physics and the method of calculation. Secondly, the fitting of the model energy distributions to observations can be used to obtain values for fundamental stellar parameters such as effective temperatures and surface gravities. Although the values so obtained are not fundamental determinations, they can be very valuable as a supplement to the fundamental results. The fundamental measurements of effective temperatures are limited to only a few stars because of the paucity of well-measured angular diameters, particularly for certain regions of the HR diagram. There are similar limits to the numbers of fundamental determinations of surface gravities. The non-fundamental results can thus be a valuable supplement if they are properly calibrated by reference to such fundamental determinations as do exist. Reviews of this subject may be found in a number of places in the literature. For a discussion of the fundamental determination of effective temperatures and bolometric corrections, see Hayes (1978). For a discussion of the interplay between the calibration of energy distributions and the understanding of the physics in model atmospheres, see Mihalas (1975). For a discussion of the determination of fundamental parameters of stars through the use of model atmospheres, see Gustafsson and Graae-Jørgensen (1985), in this symposium, and references therein. The model atmospheres appear to fit the observations best for A-type and late B-type stars. For a discussion of these and related problems for the A-stars, see Wolff (1983), and references therein.

I will discuss several measurements of the absolute flux and energy distribution of Vega in the "visual" range; these "modern" measurements now agree very well. I will also discuss what has been done in the IR between 1 and 4 μm; here the agreement is not so good. I will discuss the secondary standard stars briefly later on. I will also discuss another bright and important star: the Sun. The Sun is a special case; it is measured absolutely and without any reference to any other star, except in rare (and generally unsuccessful) cases. The measurement of the energy distribution and flux of the Sun is very difficult because of its extreme brightness, and yet it is very important because this extreme brightness (along with its large angular size) has made possible very detailed astrophysical investigations which we wish to relate to other stars. The interagreement of some of the various energy distributions and fluxes for the Sun which have been published is good, while others disagree strongly. Nevertheless, there does seem to be good reason to prefer the monochromatic flux distribution by Neckel and Labs (1984, 1985). I will discuss this situation, below.

2. THE ENERGY DISTRIBUTION AND FLUX OF VEGA

The absolute measurement of the flux and energy distribution of Vega is carried out by comparing Vega with a terrestrial source of radiant energy whose monochromatic flux is known. The absolute measurement of the flux and energy distribution of Vega or some secondary standard is often called a calibration, or even "absolute calibration" of the flux and energy distribution, and I will often use this term here. In relative photometry, a star is compared with a standard star in such a way as to minimize the difference between the method or circumstances of measuring the two stars. In the case of comparing Vega and a terrestrial source, the success of the comparison depends upon making the measurement of the star and the standard source as nearly the same as possible, or in accounting for the differences. Two geometries have been used: 1) the most common geometry used in the "visual" is to place the standard source a few hundred meters from the telescope such that the telescope may be pointed at the source and the measurement made in the same way as for a star; 2) the most common geometry used in the IR involves placing the standard source in the dome and introducing the light from it into the optical system after the telescope. In the first case, the optical system is the same for the star and source, except for a generally small differential vignetting due to the fact that the source will not be at optical infinity for the telescope. The difficulty is that there will be significant atmospheric extinction between the source and the telescope when the distance is large enough to place the source near enough to optical infinity to satisfy the condition that the source and star be measured in the same way. In the second case, obviously, the optical system will not be the same for the source and the star, and the effects of the different optical components and geometry must be carefully evaluated.

The terrestrial standard sources have been of two types: 1) a blackbody, and 2) a tungsten striplamp, operated at a specified current. The blackbodies which are used for this purpose have a small chamber surrounded by a pure metal whose melting point is used to define the temperature of operation; a small hole in the chamber is the source of blackbody radiation. The blackbodies used for astronomical calibrations usually operate at the copper-point or platinum-point (primary gold-point blackbodies are too expensive and generally too large to use in typical observatory locations). The platinum-point is preferable because its temperature is higher (2042°K), which gives more light in the UV. Copper-point (1358°K) and gold-point (1338°K) blackbodies are difficult to use below 4000Å. On the other hand, platinum-point blackbodies are more difficult to construct and their melting point has not been well known until recently. The striplamp must be calibrated at a standards laboratory; most often the calibration is done by comparing the striplamp with a gold-point blackbody. In the "visual," both striplamps and blackbodies have been used successfully, whereas in the infrared blackbodies have been used exclusively.

The process of carrying out a measurement of the energy distribution and flux of a star can be broken into three parts: 1) the standardization, including the provision of a terrestrial standard source whose monochromatic flux is known as a function of wavelength with adequate accuracy, 2) the comparison, involving the decision on which geometry to use, the determination of horizontal extinction (if necessary), the determination of the effects of any optical components which are not the same for the measurement of the star and the terrestrial standard source, etc., and 3) the photometry of the star and source, including photometric or spectrophotometric system and the determination of the (vertical) atmospheric extinction. All three of these parts must be done well if the final result is to come out well. In my discussion of the measurements which are found in the literature, I will discuss these three parts, as appropriate.

I will consider data resulting from six calibrations (in parentheses I give an abbreviation): 1) Hayes and Latham (H&L) (1975), 2) Tüg, White and Lockwood (TWL) (1977); 3) Terez and Terez (T&T) (1979), 4) Kharitonov, et al. (KHAR) (1980), 5) Terez (1982) and 6) Arkharov and Terez (A&T) (1982). In the case of H&L, the data represent the result of a discussion and combination of data from three calibrations: the measurement of the energy distribution between 3200 and 10870Å at Lick Observatory by Hayes (1970), the measurement of the monochromatic flux at 31 wavelengths between 3300 and 10800Å at Palomar Mt. by Oke and Schild (1970), and the measurement of the fluxes at 6800, 8090 and 10400Å and the energy distribution between 7100 and 10800Å at the Mt. Hopkins Observatory by Hayes, Latham and Hayes (1975). It should be emphasized that the discussion by H&L is vital to the use of these calibrations, because H&L correct the original data for errors in the treatment of horizontal extinction, and also correct it to the International Practical Temperature Scale (IPTS) of 1968, to which all the other calibrations are referred. The calibration TWL gives the monochromatic flux distribution at 90 wavelengths from 3200 to 9040Å; it was done at Lowell Observatory. The calibration by KHAR gives the monochromatic flux distribution at 23 wavelengths from 3200 to 7500Å; it was done at Alma-Ata. The calibrations reported by T&T, Terez and A&T were done during the Ararat Expedition of the Main Astronomical Observatory. They are unusual in that the standard source was located in the dome; in the other cases the standard sources were placed from about 200m to about 1100m from the telescope. The calibration by T&T also includes data taken at the Crimean Astrophysical Observatory and reports fluxes at seven wavelengths, of which I have used only the flux at 5556Å. The wavelength coverage of Terez and A&T will be discussed, below.

My objective here is twofold: one aspect is to compare the data in order to show the present status of our knowledge of the flux and energy distribution of Vega, and the other aspect is to combine the data to create a "mean" flux and energy distribution which may be used with greater confidence than any one of the original calibrations. I will combine the data in such a way as to derive a <u>continuous</u> energy distribution for Vega. This has not been done in the past, generally, because at wavelengths near strong lines and in the Balmer and Paschen confluences the details of wavelength setting accuracy and relative bandpass size have made the use and comparison of the data difficult, and the accuracy low. These problems will remain present with this new energy distribution, so it must be used with caution, particularly in the regions of the Balmer and Paschen confluences. There is now a demand for continuous energy distributions because of the increasing use of array detectors, and this continuous energy distribution will be useful for calibrating them. There is now an increasing need for continuous energy distributions of stars for synthetic photometry (Hayes 1975, Buser 1978a, 1978b, Buser and Kurucz 1978, and Buser and Kurucz 1985), and continuous energy distributions are needed for a large number of stars for this purpose. They must be calibrated against Vega, so the present continuous energy distribution will provide the basis for improved results in this field. As an example, I use synthetic photometry below in the discussion of the energy distribution of the Sun. It turns out that doing the first aspect, comparing the original calibrations, requires doing the second beforehand, so I will next explain the combination of the data to form a "mean" flux and energy distribution.

Each calibration has used a different bandpass and a different set of wavelengths for their measurements, and this fact makes comparing them difficult. The bandpasses range from 10 to 100Å, and the set of wavelengths does not cover the spectrum continuously, with the exception of Terez and A&T, and TWL in certain pieces. Often the comparison is performed by interpolating with a smooth or linear curve to a common set of wavelengths, ignoring the differential line-blocking effects. The proper way to perform the interpolation is to use a continuous spectrum with a resolution several times better than the smallest bandpass to be considered. I do not have such a spectrum of Vega available, but, fortunately, Terez and A&T report the data continuously at 25Å steps over the entire wavelength range. The bandpass was also 25Å, which is wider than ideal, but it will do. In order to combine the different calibrations, I have interpolated (with approximate allowance for the relative bandpass) their reported wavelengths in the data given by Terez and A&T. From this I determine a correction to the data by Terez and A&T; I then interpolate in the correction to make it continuous with wavelength.

This correction is applied to the data by Terez and A&T to produce a continuous energy distribution which represents the energy distribution of the calibration being considered. I have then formed a weighted mean energy distribution of Vega, using the continuous energy distribution for each calibration, and the weights given in Table I in the last three columns. The final weighted mean continuous energy distribution, in terms of the relative magnitude of the monochromatic flux per unit wavelength interval, is given in Table 2. Note that I have taken the standard wavelength for normalization to be 5000Å.

With the final weighted mean continuous energy distribution of Vega in hand, we can now compare the different calibrations. I have again interpolated at the wavelengths of each calibration, and formed the differences (calibration minus weighted mean) for each calibration at its natural wavelength set. These differences are shown in Fig. 1 (3300-7500Å) and Fig. 2 (7000-10500Å). If we remember that good relative photoelectric spectrophotometry is characterized by observational errors on the order of 0.01 mag. (std. dev.), and also remember that the results shown in Figs. 1 and 2 include possible systematic errors characteristic of absolute calibrations, then we can conclude that the agreement shown here is superb. In particular, the agreement between 4000 and 8500Å shows that the standardization of these five calibrations is excellent. We have included here, a) tungsten striplamps calibrated in Heidelberg (Lick), Washington D.C. (Palomar) and Leningrad (Alma Alta, Crimea and Ararat Expedition), b) copper-point blackbodies following an NBS design (Palomar, Mt. Hopkins, Lowell), and c) a platinum-point blackbody of original design (Lowell), which also has been compared with a gold-point blackbody. One of the copper-point blackbodies (Lowell) was also compared with a gold-point blackbody with excellent results. Note, that Hayes, Oke and Schild (1970) directly compared the striplamps used in the Lick calibration with the striplamp used in the Palomar calibration, and found excellent agreement. There are some signs of problems, here: Terez departs significantly in the UV below 3400Å, KHAR departs significantly at 4000 and at 7000Å, and TWL departs significantly around 5900A and 8700-8800Å. In the case of the departures by Terez in the UV, they were recognized by the author and he had no explanation; neither do I. The departures by TWL around 5900Å appear to involve the end of the range of an order-separation filter; perhaps low signal levels or the leakage of extraneous light are the problem. The departures by TWL at 8700-8800Å are probably due to mismatching of wavelengths and bandpasses near high-order Paschen lines, and may very well be artifacts of my comparison process. The data shown in the two figures was constructed in the two wavelength ranges 3300-7500Å and 7000-10500Å because Terez and A&T report their data split in this way. In order to see if there is any systematic shift between the two pieces, I have compared the continuous weighted mean against H&L in Fig. 3 for the full wavelength range. Clearly, the agreement is excellent, and there is no evidence of a systematic shift of the "red" and "blue" pieces greater than reasonable observational error.

I next consider the flux of Vega. There are five calibrations to consider, including the same authors as represented above. H&L include the flux measurements by Oke and Schild (1970) made at Palomar; Oke and Schild measured the monochromatic flux at all 31 wavelengths but report a result at 5556Å; this value is used here. H&L also include fluxes by Hayes, Latham and Hayes (1975) made at Mt. Hopkins at wavelengths of 6800, 8090 and 10400Å. The energy distributions by Hayes (1970) and by Oke and Schild (1970) were used to derive a weighted mean flux at 5556Å. TWL also measured the monochromatic flux at all of their wavelengths, but also report a final flux measurement for 5556Å. T&T report flux measurements made at seven wavelengths; I use here a value for 5556Å which is the mean of their values from observations at the Crimean Astronomical Observatory and at the Ararat Expedition of the Main Astronomical Observatory. The calibrations KHAR and Terez report fluxes for 5556Å, although this was not one of the wavelengths at which fluxes were measured. These results, in ergs/cm^2/sec/Å, are given in Table I, and the weights used in calculating the mean are given in the following column headed by the letter "f." The formal error (std. dev.) is only about 1.5%, which is excellent agreement for six absolute flux measurements. In Table II, the energy distribution is normalized at 5000Å, whereas in Table I I derive the flux at 5556Å. Combining these two sets of data allows calculating the flux per unit wavelength interval at 5000A to be 4.65 x 10^{-9} ergs/cm^2/sec/Å.

I would like to summarize the results of the discussion of the flux and energy distribution of Vega in the "visual" in the following way. Let us consider the usual observational errors found in good spectrophotometry; these are, as stated above, about 0.01 mag. The measurements of the absolute flux and absolute energy distribution of Vega involve much of the same observational errors as normal spectrophotometry. They involve, in addition, possible systematic errors, which can be of any size. I will characterize the efforts of a series of calibration measurements as mature when there is a statistically useful number of calibrations and the systematic agreement is on the order of the internal error, as is true for Vega in the "visual." In the case of the IR for Vega there appear to be systematic errors several times the size of the photometric errors, and in the case of the "visual" for the Sun there are not enough calibrations; in neither case can the accumulated calibrations be said to be "mature."

In the case of the IR between 1.0 and 4.0 μm, there are fewer calibrations to consider: 1) Walker (1969), 2) Selby, et al. (1983) and 3) Blackwell, et al. (1983). Walker's calibration was carried out at the Agassiz Station of the Harvard College Observatory, in Massachusetts. The blackbody was mounted in the adaptor between the photometer and the telescope, and was operated at a temperature of 402K. Measurements were made at wavelengths of 1.06, 1.13, 1.63

and 2.21 µm, with "equivalent widths" of .077, .114, .173 and .271 µm, respectively. The calibrations by Selby, et al. and Blackwell, et al. were carried out at Tenerife in 1980 and 1981, respectively with essentially the same equipment. The standard source was a furnace mounted between the telescope and the photometer, and the 1980 and 1981 observations differed with respect to the methods used to control the intensity of the furnace relative to the star. Observations were made at 2.20 and 3.80 µm in 1980, and 1.24, 2.20, 3.76 and 4.6 µm in 1981. The halfwidths were .034, .054, .145 and .323µm at the 1981 wavelengths, respectively. The furnace was calibrated against a standard blackbody. The calibration is ultimately traced back to the National Physical Laboratory, Teddington.

In each case, only a few wavelengths have been calibrated, and they are not wavelengths used in any commonly used system except where they are close to wavelengths in the standard JHKL system; in the latter case the bandpass is narrower, even where the wavelength is close to one of the effective wavelengths of JHKL. Because the calibrations are few and their wavelengths widely spaced, the approach used for the "visual" range is not appropriate. In order to have a reference spectrum for Vega I have used an ATLAS model (Kurucz 1979) which fits the "visual" energy distribution well. The model I have used is the (9400, 3.95, 0.00) model proposed by Kurucz to be a good fit to the Vega energy distribution. The fit to my new weighted mean is good, as can be seen in Fig. 4. The discrepancy between 4000 and 5000Å is disturbing, and would be interesting to investigate further. It is not my purpose, here, to discuss model atmosphere energy distributions, so I will pass it by. Except for that region, however, the fit of the ATLAS model is good, systematically. I use the IR energy distribution of this model for reference in Fig. 5, in which the IR flux calibrations are shown. I should emphasize that the IR measurements are made and reported as individual flux measurements, rather than as a flux plus an energy distribution. I show in Fig. 5 the weighted mean flux value given in Table III(the point is labelled "Hayes (1985)"). I also show in Fig. 5 a point for the flux calibration at 1.04µm from the Mt. Hopkins calibration by Hayes, Latham and Hayes (1975). This point is part of the data combined and reported by H&L, but is separated out and presented individually here. Note that in Fig. 5, the scale of the ordinate is coarser by a factor of two than used in the previous four figures. Clearly, the agreement is not nearly as good as in the "visual" range, and the amount of data far less. In this case, the systematic errors are significantly larger than the internal errors, and the number of calibrations are few, so I would characterize the situation as "immature."

Also shown in Fig. 5 are points representing three non-absolute calibrations. The non-absolute calibrations constructed in recent years use one of two basic assumptions: a) that the Sun has infrared colors similar to one or more solar analog stars; this assumption plus the solar absolute calibration in the infrared allows calibrating the stars, and b) that the infrared calibration can be obtained from a model atmosphere fitted to the visual energy distribution of Vega or other stars. Hayes (1979b) constructs a calibration using both of these bases and compares against the other absolute and non-absolute calibrations available up to that time. Wamsteker (1981) uses the solar-analog approach, and Koorneef (1983), as part of a critical homogenization of JHKLM photometry, has constructed a calibration which is very close to Wamsteker's, but which is based upon a constant color temperature for a star with zero color-indices. These three non-absolute calibrations are significant here because they are attempts to calibrate the JHKLM photometry, which is the closest we have to a standard system for spectrophotometry in the IR. Each one presents the flux for zero magnitude in this system; I have assumed V = +0.03 mag. and zero color indices for Vega in calculating the values shown in Fig. 5. The agreement between these calibrations is about as good (or as poor) as between the absolute calibrations discussed above. If a mean of the absolute calibrations were to be taken, it would not be well represented by any one of the three non-absolute calibrations. Overall, Koorneef's appears to be the closest, and is within roughly 0.05 mag. of such a mean. Clearly, more work needs to be done on the IR calibration of Vega (or other appropriate stars).

3. THE FLUX AND ENERGY DISTRIBUTION OF THE SUN

In principle, the measurement of the flux and energy distribution of the Sun is very similar to such measurements for Vega or any other star, but, in practice, its extreme apparent brightness (compared to the brightest of other stars) plus the fact that it is an extended source make the measurements especially difficult. The extreme apparent brightness and large angular size of the Sun also provide for some great opportunities for detailed astrophysical investigations. We would, of course, like to be able to compare the Sun with other stars in terms of measurements which are made commonly on other stars, such as the effective temperature and bolometric correction, which depend, as described above, upon measurements of the flux and energy distribution. One should note that, although the measurements of the flux and energy distribution are difficult, the angular diameter can be measured with an accuracy far better than for any other star. Since the accuracy with which the angular diameter is measured is the primary determinant of the accuracy with which the effective temperature is measured (Hanbury Brown 1985, Davis 1985), the result is that the effective temperature is better known for the Sun than for any other star.

As is true for other stars, the flux and energy distribution are also important for comparison with model atmospheres of the Sun; this case is very important because the models may be compared with other observations with a detail which cannot be achieved for other stars. Because the Sun can be observed so well in other ways, it is particularly important that the models be a good fit, and that means that it is particularly important that the energy distribution be well measured. The present status of model atmospheres for solar-type dwarfs is discussed by Gustafsson and Graae-Jørgensen (1985) in this symposium.

The measurement of the flux and energy distribution of the Sun have been the object of much effort in recent decades, but the result has been a number of highly discordant results. There has been an active controversy about whether making observations from a high-altitude aircraft improves the measurements. The assertion by the proponents is that atmospheric extinction is the major contributor to systematic errors in the ground-based observations; the alternate assertion is that the difficulties of doing the standardization and the comparison will dominate because of the environment in the aircraft and the restricted time available in which to do the observations. In fact, the restricted time available in which to do the observations makes the measurement of what atmospheric extinction there is (and it is not negligible) more difficult. The results seem to bear out the proponents of the ground-based measurements. I do not wish to review all the recent measurements nor to go through this controversy in detail, because this effort has been undertaken by myself and many others already, and the results have been published (Makarova and Kharitonov 1972, 1976; Neckel and Labs 1973, Labs 1975, Pierce and Allen 1977, Hayes 1979a, Hardorp 1980 and Taylor 1984a). I am most interested in discussing the recent publication by Neckel and Labs (1984; see also Neckel 1984 and Neckel and Labs 1985), which gives the monochromatic flux continuously with wavelength from 3300 to 12500Å, with bandpasses (and wavelength steps) of 10Å (3300-6300A), 20Å (6300-8700Å) and 50A (8700-12500Å). This work is based upon ground-based results; the primary basis being measurements of the intensity of the center of the solar disc made from the Jungfraujoch Scientific Station. The standard source was a blackbody. This investigation demonstrates the special demands made upon attempts to calibrate the solar spectrum; since the original measurements the authors have spent considerable effort on obtaining the data needed to determine the flux from the entire solar disc, based upon the intensity of the center. Their most recent efforts involve new limb-darkening and high-resolution FTS spectrum measurements made at the Kitt Peak National Observatory.

A comparison and averaging of solar data in a manner like that used above for Vega in the "visual" region is not appropriate in the solar case, because of the large scatter in the solar data. I note that the aircraft data by Arveson, et al. (1969), corrected for a revised lamp calibration reported by Duncan (1969), is compared with an earlier version of the Labs and Neckel (1968, 1970) data by Labs (1975) and by Hardorp (1980); the comparison shows good agreement from 4000 to 8000Å and from 1 to 2μm. Recent measurements of the monochromatic flux of the Sun at ten wavelengths between 4100 to 10100Å, made at Mauna Kea (Shaw and Fröhlich 1979) and from a stratospheric balloon (Fröhlich and Wehrli 1981) agree with a preliminary version (Neckel and Labs 1981) of the new data by Neckel and Labs excellently - with a standard deviation of 1.2% (Fröhlich 1983; Neckel 1984). Interference filters of typically 70Å bandpass were used with silicon diode detectors. The radiometers at eight wavelengths were calibrated against a tungsten striplamp which had, in turn, been calibrated by the NBS. At two wavelengths, the radiometers were calibrated at the Physikalisch-Meteorologisches Observatorium, World Radiation Center, Davos, Switzerland, by using dye lasers as intermediate standards, referenced to an electrical cavity radiometer (Fröhlich 1983, Shaw 1982).

The agreement described above with the data by Arvesen, et al. (1969) and by Fröhlich and his collaborators, plus the concensus of the discussions of older data cited earlier, leads me to conclude that the new data by Neckel and Labs is probably accurate to something like ±1-2% (std. dev.) over the entire wavelength range covered (and perhaps better). The fact that there are no other calibrations of the solar monochromatic flux as a function of wavelength which cover the entire wavelength range with a resolution and continuity comparable to theirs means that one cannot be as confident as in the case of Vega. Thus, I have tried to make other comparisons which might test, if only roughly, the systematic accuracy of the new Neckel and Labs data.

The first test I have performed is to compare the N&L data with the energy distribution of two "solar analogs" which are calibrated with respect to my new energy distribution of Vega. I have chosen the double star system 16 Cyg A & B (HR 7503 and 7504), which has been analysed by Perrin and Spite (1981), who concluded from high dispersion spectra covering 4300-6000Å that 16 Cyg B was "indistinguishable" from the Sun in terms of effective temperature, surface gravity and chemical composition, and that 16 Cyg A was "somewhat hotter," with a "smaller gravity." They used spectra of the Moon for their solar reference. I have used the scans by Taylor (1984a), covering 3288-7000Å continuously with passbands of 49Å (3288-5304Å), 32Å (5248-6182Å) and 100Å (6050-6950Å), and corrected from the calibration of Vega by Hayes and Latham (1975) to that of this paper. I have made a very rough allowance for the difference in passband sizes of the data for Vega, 16 Cyg A & B and the Sun, but I am clear that bandpass mismatches represent a major difficulty in the comparison I have made here. I smoothed the data by Neckel and Labs roughly to Taylor's bandpasses and interpolated to Taylor's passband centers. The differences (16 Cyg A minus the Sun) and (16 Cyg B minus the Sun) are shown in Figure 6. The agreement is here very good systematically, but there are problems which lead me to recommend that this comparison be carried through more carefully and for more stars. The excursion of about 0.06 mag. at about 3500Å is somewhat disturbing, as are the "waves" in the data through the rest of the spectral range, but these effects may well be due to the problems of matching bandpasses and wavelengths. In any case, considering the number of steps involved, the agreement does show that there is a meaningful degree of coherence between the calibrations of the Sun and Vega.

The next comparison is, in some respects, weaker yet, but also shows to a useful degree the coherence between the calibrations of the Sun and Vega. I have calculated synthetic values of V and (B-V) for the Sun using a method which I have described earlier (Hayes 1975, 1979a). This method involves convolving the response functions of the B and V filters as recommended by Ažusienis and Straižys (1966) with the Neckel and Labs monochromatic flux distribution of the Sun. The transformation coefficients in (B-V) were determined by fitting synthetic values of (B-V) with observed ones for energy distributions of sample spectral types from B0 to M0 given by Straižys and Sviderskienė (1972); the latter were converted to the calibration of Hayes and Latham (1975) which is for this purpose indistinguishable from the calibration derived in this paper. The observed mean colors for each spectral type are from Johnson (1966). I have shown (Hayes 1975) that one must use such a wide range of spectral type in order to obtain a trustworthy value for the transformation coefficients unless one is concerned with a very narrow range of spectral type. The zero-point in V was determined from the energy distribution and flux of Vega, itself, derived earlier in this paper. The synthetic values of V and (B-V) for the Sun and Vega are given in Table III. The value of (B-V) for Vega of -0.016 mag. is a good indication of the maximum systematic error which one can expect from this method, when good energy distributions are used. Thus, I would associate an error of about 0.02 mag. with the final synthetic values of V and (B-V) of the Sun, -26.75 and +0.661 mag. respectively.

I must compare the synthetic photometry with observations of the Sun, and this clearly is the weak point of the comparison, because direct photometric measurements of the Sun are very difficult because of its extreme brightness, compared to the stars for which UBV photometers were designed to measure. There have been a number of determinations of the apparent visual brightness of the Sun, but I find only three which have been made photoelectrically: that by Nikonova (1949), transformed to the V-magnitude scale by Martynov (1960), that by Stebbins and Kron (1957), corrected by myself for an error in the treatment of horizontal extinction (see Hayes and Latham 1975) and that by Gallouët (1964). Their values are summarized in Table IV. Similarly, there are only a few photoelectric determinations of (B-V) for the Sun. Stebbins and Kron (1957), measured color in the six-color system of Stebbins and Whitford; I have transformed their results into (B-V) (Hayes 1979) and do not find the use of the six-color system and the need to transform it into the UBV system a significant problem in this context. Additionally, there are the measurements by Gallouët (1964), Preski (1970) and Tüg and Schmidt-Kaler (1982). Their results are also summarized in Table IV. The mean values for these observations are -26.75±0.06 and +0.661±0.03 mag.

The exact agreement of the values of V and (B-V) at the ends of the last two paragraphs is accidental, of course, but the fact that the agreement is good is an indication of a significant degree of coherence in the calibrations of the Sun and Vega. I wish also to point out that the interagreement of the photometric observations, which is the basis of the error figures I attach to the means, is not nearly as good as the internal errors quoted by the authors. For example, all four measurements of (B-V) quote internal errors of 0.01 mag., and yet the range is 0.06 mag! Clearly, there are significant systematic errors in these measurements. One can reduce the systematic error in the mean of a series of such measurements if there are enough of them and if they are all really measuring the same thing; in this case the averaging of only four measurements does not guarantee that the mean is free of significant systematic error. On the other hand, the fad of determining the value of (B-V) of the Sun from spectroscopic measurements misses the point: our objective is to determine the photometric behavior of the Sun!

I would like to conclude this section by recalling my earlier characterization of the calibration of Vega in the "visual" range as "mature," whereas I concluded that the calibration of the calibration of Vega in the IR is yet "immature." In the case of the calibration of the Sun in the "visual" range, the calibration is yet immature, even though the new calibration of the Sun by Neckel and Labs is probably as accurate as the calibration of Vega! The reason for my characterization of the calibration of the Sun as "immature" is that there are not a large enough number of calibrations which agree at a level close to their internal errors. Thus, we do need more excellent calibrations of the Sun, in addition to what we have.

4. THE POSSIBILITY OF VARIABILITY IN VEGA

Since Vega is used as the primary standard star for the measurements of stellar energy distributions and fluxes, it is important to consider the possibility that it is a variable star. As Batten (1985a) puts it, a standard star should be: "constant in the characteristic for which it has been chosen as a standard, within the smallest attainable errors of measurement." There have been reports in the literature for over 50 years of observations of variable brightness, spectrum and radial velocity for Vega. A useful summary of the history of these reports has been published by Wisniewski and Johnson (1979); their concern about this topic was spurred by their apparent discovery of emission lines in the near infrared spectrum (Johnson and Wisniewski 1978). These emission lines have not been confirmed by other observers (Barker et al. 1978; Griffin and Griffin 1978), and their relevance to the use of Vega as a spectrophotometric standard is purely circumstantial. The earliest observations of brightness variations include those by Guthnick, who built the first successful photoelectric photometer, and who used the new photometric technique to observe Vega from 1915 to the 1930's. He reported variations with an amplitude of a few hundredths of a magnitude over characteristic times of variation of hours to months (Guthnick 1918, 1930a, 1930b, 1930c, 1931). It must be remarked, on the one hand, that these observations should not be rejected solely because of their age. On the other hand, they should be treated with considerable caution, because the photometric equipment and technique used were primitive and the observing site marginal for photometry. The amplitudes he reports cannot be much larger than his internal errors. More recently, the long series of UBV observations by H. L. Johnson and his collaborators shows residuals larger than some other bright stars, and if interpreted as evidence of variability, then the amplitude would be several hundredths on a magnitude (Johnson 1980; Wisniewski and Johnson 1979). Kharitonov, et al. (1980) have performed absolute energy distribution and flux measurements on eight secondary standard stars similar to that discussed above for Vega. They have cross-compared the observations, made during 1977 and 1978, of all the stars, including Vega, and found evidence of variability of Vega on the order of 0.02 to 0.05 mag. Kozyreva, Moshkalev and Khaliullin (1981) have reviewed some of the literature, and have reported their own observations. These are WBVR photoelectric photometry made at an altitude of 3 km, covering three months during 1980. They say that the observations "showed no brightness variations significantly exceeding the measurement error (σ = 0.006 mag.)," but the data "indicates the possibility of (quasi) periodic microvariability of Vega with an amplitude of ∿0.02 mag. and a period (characteristic time) of about an hour." Their mean value for the V magnitude (V = 0.034 mag.) agrees well with the results in the literature. Fernie (1981) made photoelectric observations on 14 nights over four months in 1980. He used a mask on the telescope only for observations of Vega. On one night Vega appeared to be brighter by 0.041 mag; two other nights had brightenings of about 0.015 mag. On the remaining nights the star was constant to about 0.006 mag. Glushneva (1983b) reports that Sperauskas in 1983 described photoelectric observations covering three seasons during which variations did not exceed 0.01 mag. Finally, I can report unpublished IR observations made at Kitt Peak which also do not show evidence of variability. R. R. Joyce has made 10 JHKL measurements of the difference in brightness of Vega and γ Lyr over the 3 1/2 year period from October, 1980 to March, 1984, and finds an overall standard deviation of 0.007 mag. Measurements have been made in a nearly monochromatic photometric system which has 13 wavelengths between 1.04 and 4.0 μm by the author and R. F. Wing, S. T. Ridgway, R. R. Joyce and C. P. Rinsland (Hayes, et al. 1980, Hayes, et al. 1983). Twenty-nine scans of Vega were made on 27 dates between December, 1979 and November, 1982, and were reduced in a network with 46 other stars. Because of the way the observations and reductions were made I cannot give a precise value for the limit on the variations of Vega, but they must be less than 0.01 mag. In summary, there is some evidence for low-amplitude variations in the brightness of Vega, but it results from the less-controlled or older observations; the more recent observations with the most appropriate observational techniques do not show variability on a scale which would be important, here. I should also note that the six absolute flux measurements which I discussed above cover a period of time of over ten years and have a standard deviation of only 1.5%.

As noted above, there have also been reports of radial-velocity variations; some of these and the history are discussed by Wisniewski and Johnson (1979). Clearly, evidence of pulsation would be relevant here, but the evidence is far from definitive. In fact, reports of unpublished observations, given at this symposium by Batten (1985b) and Walker (1985) indicate that no variability of the radial velocity is present on a scale which would be significant, here.

My overall conclusion is that the evidence for variability in Vega is not strong enough to indicate a need for a program to find and begin observing a substitute primary spectrophotometric standard star. I think the evidence is strong enough that we should be aware of the possibility of variability, so that we make observations and encourage our colleagues to make observations which will help decide the issue. Photometric observations of this type are needed for many of the brightest stars, and I would like to encourage the photometrists in the audience and the readership to undertake them, if they are so inclined.

5. THE SECONDARY STANDARD STARS

My concern in this Section is the availability of secondary standard stars which can be used when Vega is not visible or is too bright. The secondary standard stars which are in use today are, for the most part, standards for energy distribution measurements but not for fluxes; as noted above fluxes for stars other than Vega and the Sun are usually obtained by use of the V magnitude relative to that of Vega. I will henceforth only consider standards for measurements of energy distributions. A secondary standard star should have an energy distribution measured with a photometric accuracy which is close to that of Vega; one finds stars in the literature which are used as standards which are simply taken from one or more of the many catalogues of stars with measured energy distributions. Certainly, without a critical evaluation of energy distributions from several sources this procedure is very dangerous. I can recommend here only stars which are well-measured several times and critically evaluated as secondary standards.

After reviewing the lists of secondary standards to be found in the literature, one can conclude that while there are some truly useful lists of such stars available, there is not enough unity to make such lists universally valuable. For example, observers in the Soviet Union mostly use secondary standards from lists containing seven or eight bright stars (Kharitonov and Glushneva 1978, Kharitonov, et al. 1980, Voloshina, Glushneva and Shenavrin 1980 and Glushneva and Ovchinnikov 1982). Observers in the Western countries have mostly used the 11 secondary standards proposed by Breger (1976). Taylor (1984b) has recently published a list of 16 secondary standards which include, and supersede, Breger's. I have made a preliminary attempt to compare the Soviet and Western lists, but there are only two stars in common (α Leo and η UMa) in the "blue" spectral region. The agreement between the energy distributions by Taylor and by Glushneva and Ovchinnikov (1982) appears to be very good. In the "red" γ Ori is common, as well, and the agreement between the energy distributions by Taylor and by Voloshina, Glushneva and Shenavrin (1980) is not so good, especially at the longer wavelengths.

I have not carried out the comparison above in any greater detail because of the lack of an adequate number of overlapping stars, and because the wavelength sets are so different that a detailed comparison using continuous spectra would be needed. I recommend strongly that the Soviet and Western observers include each other's secondary standard stars in their observing programs, so that this comparison can be carried out properly. Having made the comments above, I can call attention to the very useful combined list of secondary standards published by Glushneva (1983a) and the supplementary list by Burnashev (1984).

In addition to the bright secondary standard stars discussed in the previous paragraphs, there is an intensifying need for faint standards. An early list of such standards is by Stone (1974, 1977); the stars are between 10th and 12th mag. The recent publication of four secondary standards by Oke and Gunn (1983) is very important; the stars are F subdwarfs between 8th and 10th mag., and they have been very carefully calibrated against Vega. The energy distributions are continuous, as well. Hayes and Philip (1984) have compared their observations of five stars observed at Palomar using BD +17° 4708, Oke and Gunn's "primary" secondary standard, with their observations at Kitt Peak and Cerro Tololo using Breger's secondary standard stars; the comparison shows excellent agreement. This means that between 3400 and 6800A the standards by Oke and Gunn are on the same system as those by Breger. Hayes and Philip (1985) have made a comparison which indicates that Taylor's energy distributions will give, if anything, improved agreement. Other lists of fainter secondary standards include those by Stone and Baldwin (1983) and Baldwin and Stone (1984) for the southern sky. There is no overlap with any other lists of faint secondary standards, so comparison is impossible. Hayes and Philip (1985) also give a list of faint (7th to 12th mag.) and fainter (15th to 16th) secondary standards. Another list is that by Ipatov (1983), which includes 10 stars between 7th and 9th mag. There is only one star in common with any other list.

The situation in the IR is similar, in some respects, to that for the bright stars in the "visual." First, I note that the absolute calibrations discussed above do not reproduce any standard combination of bandpasses and wavelengths. Second, however, it should be noted that there is not one JHKL system, but several, since a number of observatories are using instrumentally defined systems and their own sets of standard stars (Glass 1973, 1974a, 1974b, Wamsteker 1981, Elias, et al. 1982, Allen and Cragg 1983 and Joyce, Probst, and Guetter 1984). Clearly, a true spectrophotometric system in the IR is needed; we have one in process at Kitt Peak (Hayes, et al. 1980, Hayes, et al. 1983) in which 47 stars have been observed at 13 nearly monochromatic wavelengths between 1.04 and 4.0 μm. The publication of this system is waiting upon the completion of an absolute calibration.

CONCLUSIONS

The calibration of the energy distribution of Vega has matured in recent years, and the mean energy distribution and flux given in this paper can be recommended as having an accuracy on the order of 1.0 to 1.5% over the wavelength range 3300 to 10500Å. On the other hand, the secondary standards need more work, in that more overlap between the various lists (both bright and faint) in use is badly needed. The calibration of the IR, and the availability of secondary standard stars in the IR, is yet immature, and I recommend more effort in this wavelength range. The calibration of the energy distribution of the Sun, again, is probably now quite accurate, and is apparently quite coherent with the new energy distribution of Vega, but the lack of a number of co-equal calibrations leads to a lack of confidence which would be best remedied by having more such calibrations.

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TABLE I

WEIGHTS AND FLUXES FOR CALIBRATION OF VEGA

Calibration	flux, E-9	f	Weights 3300–7500	7000–9040	9040–10500
HAYES AND LATHAM (1975)	3.39	2	2	2	2
TUG, ET AL. (1977)	3.47	1	1	1	–
TEREZ AND TEREZ (1979)	3.42	1	–	–	–
KHARITONOV, ET AL. (1980)	3.54	1	1	–	–
TEREZ (1982)	3.44	1	1	–	–
ARKHAROV AND TEREZ (1982)		–	–	1	1
Mean	3.44 ± 0.05				

TABLE III

BV SYNTHETIC PHOTOMETRY OF THE SUN AND VEGA

	$(B-V)_{SYN}$*	V_{SYN} + CONST	V_{OBS}	V_{SYN}
VEGA	− 0.016 MAG	− 7.738 MAG	+ 0.03 MAG	—— MAG
SUN	+ 0.661	−34.515	——	−26.75 MAG

*$(B-V)_{SYN}$ = 1.00(b−v) + 1.09 MAG. (HAYES 1975), FOR THE RESPONSE FUNCTIONS BY AŽUSIENIS AND STRAIŽYS (1966).

TABLE IV

DIRECT PE DETERMINATIONS OF V, (B−V) OF THE SUN

SOURCE	V (MAG)
NIKONOVA (1949)*	−26.81 ± 0.05
STEBBINS AND KRON (1957) HOR. EXT. CORR. BY HAYES	−26.75 ± 0.03
GALLOUËT (1964)	−26.70 ± 0.01
MEAN	−26.75 ± 0.06
	(B−V) (MAG)
STEBBINS AND KRON (1957)+	+ 0.627 ± 0.01
GALLOUËT (1964)	+ 0.68 ± 0.01
TÜG AND SCHMIDT-KALER (1982)	+ 0.686 ± 0.01
PRESKI (1970)	+ 0.65 ± 0.01
MEAN	+ 0.661 ± 0.03

*TRANSFORMED TO V-MAG BY MARTYNOV (1960).
+TRANSFORMED TO (B−V) BY HAYES (1979).

TABLE II

ENERGY DISTRIBUTION OF VEGA

λ	Mag(f_λ)	λ	Mag(f_λ)	λ	Mag(f_λ)	λ	Mag(f_λ)
3300	.358	5100	.064	6900	1.049	8700	1.706
3325	.378	5125	.079	6925	1.063	8725	1.860
3350	.391	5150	.095	6950	1.069	8750	1.899
3375	.393	5175	.110	6975	1.081	8775	1.762
3400	.395	5200	.126	7000	1.088	8800	1.717
3425	.406	5225	.139	7025	1.101	8825	1.835
3450	.419	5250	.154	7050	1.115	8850	1.940
3475	.430	5275	.167	7075	1.129	8875	1.810
3500	.439	5300	.183	7100	1.141	8900	1.762
3525	.442	5325	.192	7125	1.156	8925	1.762
3550	.445	5350	.206	7150	1.171	8950	1.774
3575	.453	5375	.221	7175	1.181	8975	1.885
3600	.458	5400	.234	7200	1.191	9000	2.102
3625	.463	5425	.249	7225	1.201	9025	2.102
3650	.459	5450	.264	7250	1.212	9050	1.925
3675	.455	5475	.278	7275	1.226	9075	1.859
3700	.452	5500	.296	7300	1.241	9100	1.872
3725	.414	5525	.311	7325	1.252	9125	1.898
3750	.265	5550	.324	7350	1.264	9150	1.995
3775	.105	5575	.333	7375	1.273	9175	2.102
3800	-.060	5600	.349	7400	1.281	9200	2.220
3825	-.191	5625	.368	7425	1.293	9225	2.238
3850	-.342	5650	.384	7450	1.305	9250	2.118
3875	-.454	5675	.399	7475	1.316	9275	1.953
3900	-.438	5700	.415	7500	1.327	9300	1.912
3925	-.555	5725	.426	7525	1.340	9325	1.925
3950	-.469	5750	.441	7550	1.349	9350	1.939
3975	-.415	5775	.456	7575	1.364	9375	1.953
4000	-.595	5800	.471	7600	1.372	9400	1.953
4025	-.680	5825	.479	7625	1.387	9425	1.981
4050	-.669	5850	.498	7650	1.395	9450	2.024
4075	-.502	5875	.513	7675	1.404	9475	2.117
4100	-.364	5900	.529	7700	1.421	9500	2.256
4125	-.460	5925	.545	7725	1.429	9525	2.371
4150	-.581	5950	.561	7750	1.437	9550	2.372
4175	-.568	5975	.575	7775	1.453	9575	2.184
4200	-.553	6000	.592	7800	1.462	9600	2.070
4225	-.541	6025	.606	7825	1.470	9625	2.024
4250	-.520	6050	.619	7850	1.478	9650	2.010
4275	-.487	6075	.630	7875	1.487	9675	2.024
4300	-.393	6100	.642	7900	1.496	9700	2.024
4325	-.205	6125	.657	7925	1.514	9725	2.055
4350	-.208	6150	.672	7950	1.523	9750	2.085
4375	-.332	6175	.687	7975	1.533	9775	2.101
4400	-.404	6200	.702	8000	1.542	9800	2.116
4425	-.391	6225	.717	8025	1.551	9825	2.133
4450	-.375	6250	.733	8050	1.560	9850	2.132
4475	-.357	6275	.742	8075	1.570	9875	2.133
4500	-.340	6300	.754	8100	1.580	9900	2.148
4525	-.316	6325	.769	8125	1.589	9925	2.165
4550	-.272	6350	.779	8150	1.599	9950	2.217
4575	-.280	6375	.785	8175	1.620	9975	2.272
4600	-.270	6400	.793	8200	1.630	10000	2.349
4625	-.256	6425	.810	8225	1.640	10025	2.477
4650	-.240	6450	.824	8250	1.650	10050	2.596
4675	-.219	6475	.839	8275	1.662	10075	2.389
4700	-.199	6500	.859	8300	1.673	10100	2.329
4725	-.179	6525	.957	8325	1.683	10125	2.271
4750	-.157	6550	1.064	8350	1.695	10150	2.251
4775	-.140	6575	1.109	8375	1.705	10175	2.233
4800	-.119	6600	.992	8400	1.717	10200	2.215
4825	-.034	6625	.908	8425	1.739	10225	2.233
4850	.134	6650	.920	8450	1.750	10250	2.233
4875	.129	6675	.932	8475	1.762	10275	2.249
4900	.011	6700	.944	8500	1.774	10300	2.248
4925	-.049	6725	.953	8525	1.798	10325	2.267
4950	-.035	6750	.965	8550	1.810	10350	2.266
4975	-.015	6775	.978	8575	1.835	10375	2.283
5000	.000	6800	.991	8600	1.861	10400	2.282
5025	.017	6825	1.006	8625	1.810	10425	2.301
5050	.034	6850	1.022	8650	1.751	10450	2.300
5075	.048	6875	1.034	8675	1.705	10475	2.318
						10500	2.318

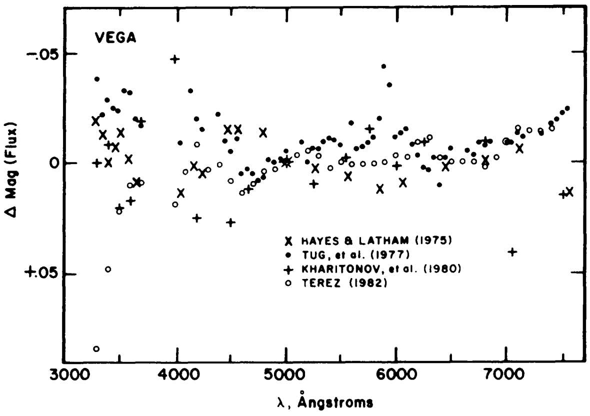

Fig. 1 The energy distribution of Vega over the wavelength range 3300 - 7500Å, referred to the weighted mean, for four sources.

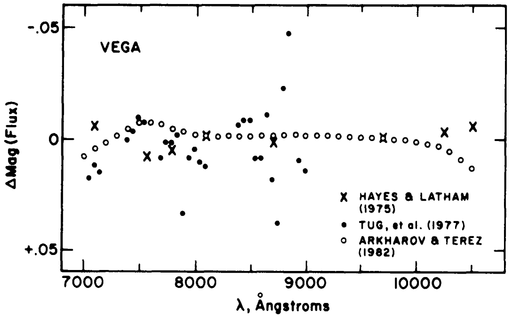

Fig. 2 The energy distribution of Vega over the wavelength range 7000 - 10500Å, referred to the weighted mean, for three sources.

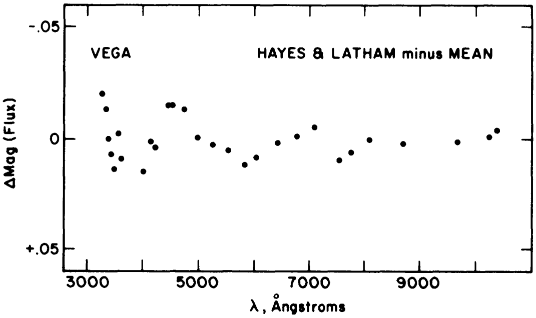

Fig. 3 The energy distribution of Vega over the wavelength range 3300 - 10500Å by Hayes and Latham (1975), compared to the weighted mean.

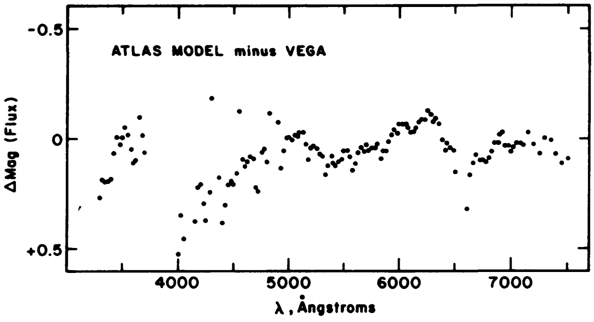

Fig. 4 An ATLAS model atmosphere (Kurucz 1979) fitted to the weighted mean over the wavelength range 3300 - 10500Å.

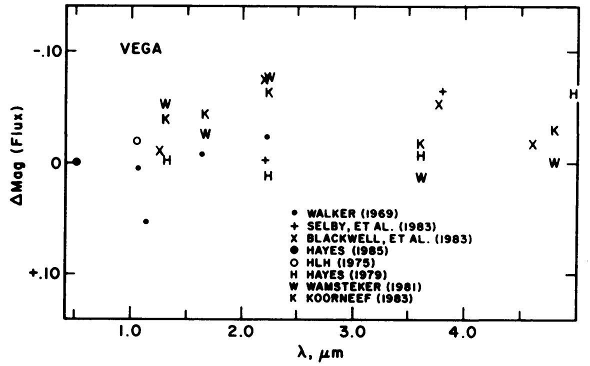

Fig. 5 The energy distribution of Vega over the wavelength range 0.55 - 4.6 μm, referred to the ATLAS model atmosphere shown in Fig. 4, for five sources.

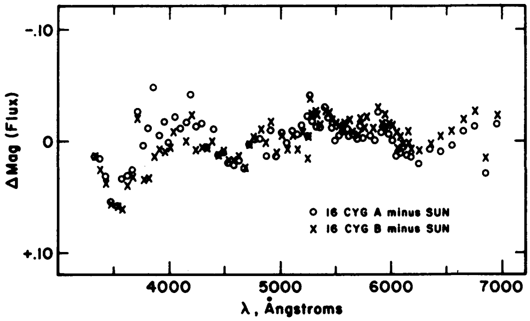

Fig. 6 The energy distribution of BS 7503 (16 Cyg A) and BS 7504 (16 Cyg B) (Taylor 1984, standardized to the weighted mean energy distribution of Vega) over the wavelength range 3300 - 7000Å, compared with the energy distribution of the Sun by Neckel and Labs (1984).

DISCUSSION

GLUSHNEVA: I want to begin the discussion with two comments. The first one concerns the possible brightness variation of Alpha Lyrae. We see that much effort has been made by a number of investigators to obtain reliable calibration data in a wide spectral range. If we delete Alpha Lyrae from the list of spectrophotometric standards as a variable star all of our spectrophotometric catalogues, including several thousand stars, lose their basis. Really we have no alternative to Alpha Lyrae as a reliable spectrophotometric standard. On the other hand, if Alpha Lyrae is really variable it would increase the errors of spectrophotometric data if a star is compared with Alpha Lyrae directly or by means of a secondary which is compared directly with Alpha Lyrae. So the importance of photometric observations of possible brightness variations of this star in the future is obvious.

My second comment concerns the reliability of the calibration in the infrared. It can be demonstrated that when we use monochromatic fluxes at the I, J, and K bands of the Johnson system for the determination of effective temperatures we find a systematic difference in the J and K determinations which must be taken into account if we use the calibration by Johnson. But if we use another calibration, for example the recent calibration data by Koorneef, the dependence of temperature on color becomes stronger.

ADELMAN: Was the Atlas model whose predictions you showed optimized for fit to the Vega calibration presented in this paper? If so, what T_{eff} and log g were used for this model and how was log g determined?

HAYES: No. I used the (9400, 3.95, 0.00) model which Kurucz proposed several years ago as a good fit to Vega.

GARRISON: I have two comments on the determination of the (B-V) color of the Sun by Tüg and Schmidt-Kaler, compared with the others. The internal errors they quote cannot represent the systematic errors. The correction for an ideal pinhole diffraction is probably not absolutely known to 1% and their pinhole is probably not perfect. Also, their observations of the Sun are made during the day and the stars for transformation at night and I am not at all convinced that the transformation can be made to only a few percent under these extreme conditions. I find that most photometry does not successfully transform even at night!

Secondly, their value is quite extreme and I can quite clearly state that stars with (B-V) of 0.69 do NOT have the same line spectrum as the Sun at 1 - 2 Ångstroms resolution. I am not saying that they are wrong, just that the difference is significant. I agree that the Tüg and Schmidt-Kaler determination is elegant and very interesting. I only question the relationship of systematic and internal errors.

HAYES: For all four of the direct measurements of $(B-V)_o$ the authors quote an internal error of 0.01 mag., and yet the spread is from 0.63 to 0.69 mag. Thus, there must be significant systematic errors in these measurements, and we do not really know which measurements are the most seriously affected. With regard to the disagreement between the result of Tüg and Schmidt-Kaler and the typical spectroscopic behavior, I agree. But I must say that the degree to which the Sun is atypical photometrically for stars of its spectral type is the interesting question.

GARRISON: With regard to your comment about using more precise photometric systems, there are people working on it. Erik Olsen in Denmark has observed many thousands of early G stars on the Strömgren system and is currently working on the mid-G stars. Chmielewski has used the Geneva system to infer the color of the Sun.

HAYES: Yes. So the next step is to make direct observations of the Sun in these systems.

BESSELL: With regard to secondary standards there are three glaring unfilled needs. We need V = 16 mag. DC stars from 0.34 to 1.1 microns for photon counting spectrophotometry. We need V = 7 - 9 mag. G and K extreme metal-deficient ($[Fe/H] \cong -2.0$) stars for CCD spectrophotometry and we need K = 3 - 5 mag solar-like dwarfs for J, H, K, L (1.2 - 4.0 micron) spectrophotometry. A and B stars with large continuum discontinuities and strong hydrogen lines are very unsuitable as spectrophotometric standards for work from 0.3 - 5 microns.

HAYES: I agree. In cases 1 and 3 work is in progress on such standards.

MILLWARD: I would just like to point out that Vega was one of our trigonometric parallax standards for the H-gamma-luminosity calibration, but had to be excluded from the group as it was found to be one magnitude too luminous for its H-gamma-equivalent width. So, in this sense it is anomalous.

HAYES: Yes. I believe this effect has been known for some time.

GALGANI: I would like to make a comment. Calibrations are important not only for applications, as discussed here, but also for general physics. Indeed there is a problem of internal consistency. Take for example the case of isochromatics; a blackbody is observed at a fixed frequency but at various known temperatures. The fluxes so obtained should fit Planck's law. I studied this problem of the internal consistency for blackbodies in the last two years and found that the situation is quite striking. Only last year a very good result was found by Quinn and Martin (one part over a thousand) but only for the global emission (determination of the Stefan-Boltzmann constant). If one, instead, looks at the spectrum for a relevant range of the variable $x = h\nu/KT$; one finds that essentially no data were published after 1921 (Rubens and

Michel) and that the data fit Planck's law within 3% (three standard deviations). My point is then that if in the calibrations one finds a consistency better than 3%, then one should publish this as an interesting result in general physics.