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SPECTRAL IRRADIANCE CALIBRATION IN THE INFRARED. I. GROUND-BASED AND *IRAS* BROADBAND CALIBRATIONS

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ABSTRACT

We describe an approach to absolute stellar calibration of broad and narrowband infrared filters based upon new models of Vega and Sirius due to Kurucz [private communication (1991)] and calculated by him, for the first time, with realistic stellar metallicities and a finely-gridded wavelength scale in the infrared. After normalizing the Vega model so that it matches Hayes' [*Calibration of Fundamental Stellar Quantities*, Proc. IAU Symposium No. 111 (1985)] weighted average of six monochromatic 5556A measurements we integrate the model through a variety of infrared filters using determinations of filter transmission profiles obtained at their actual operating temperature, and detailed model calculations for terrestrial atmospheric transmission. This provides in-band fluxes for Vega, which we define to be zero magnitude at all wavelengths shortward of 20 μm. We use existing infrared photometry differentially to establish an absolute scale for the new Sirius model. This yields an angular diameter within 1σ of the mean determined interferometrically by Hanbury Brown *et al.* [MNRAS, 167, 121 (1974)]. For practical purposes, Sirius provides the absolute calibration beyond the 20 μm region because of Vega's dust shell. Isophotal wavelengths and monochromatic flux densities for both Vega and Sirius are tabulated. We attempt a comparison of our calibration figures for the *IRAS* wavebands with the process used to generate the original *IRAS* absolute calibration. A complete duplication of that process is not currently possible. Preliminary indications are that *IRAS* is too high by 2%, 6%, 3%, and 12% at 12, 25, 60, and 100 μm, respectively.

1. INTRODUCTION

In his critical review of the optical absolute calibration of Vega, Hayes (1985) states of the corresponding situation in the infrared: "The calibration of the IR, and the availability of secondary standard stars in the IR, is yet immature, and I recommend more effort... ." Unfortunately, infrared astronomical calibration has been developed from the completely erroneous assumption that normal stars can be represented by Planck functions at their effective temperatures (although local fits to some blackbody in a restricted region may be an adequate approximation for some purposes). Recently, Cohen *et al.* (1992) have demonstrated from ratios of cool stellar spectra to that of Sirius that even early K-type stars such as α Boo are far from featureless blackbodies. In order to develop spectrally continuous absolute standards in the infrared, Cohen *et al.* (1992: hereafter CWW) have devised a technique for splicing together absolutely calibrated versions of existing spectral fragments and have demonstrated the method by producing a complete 1.2–35 μm absolutely calibrated spectrum of α Tau. Their method depends in part upon correct normalization of spectral fragments in accordance with infrared stellar photometry. In the present paper we describe the independent effort at broadband infrared calibration that supports this spectral calibration scheme.

Blackwell and colleagues have for some years applied the Infrared Flux Method to photometry of bright stars and derived effective temperatures and angular diameters by use of the MARCS model atmosphere code, and adoption of a calibration between infrared magnitudes and flux densities. In their early work these authors used the absolute mountaintop measurements of Vega (e.g., Blackwell *et al.* 1983; Selby *et al.* 1983; Mountain *et al.* 1985; Leggett *et al.* 1986; Blackwell *et al.* 1986; Blackwell *et al.* 1990). However, in their most recent paper (Blackwell *et al.* 1991), they have abandoned these ground-based measurements and have instead adopted the Vega model by Dreiling & Bell (1980). They justify this change in philosophy on the basis of the substantially tighter run of effective temperature with wavelength, for the many stars that they analyze, when using Dreiling and Bell in order to calibrate their infrared narrowband photometry, as opposed to the absolute measurements. They attribute this difference essentially to the intrinsic difficulties of the ground-based measurements. We follow the philosophy of Blackwell *et al.* (1991) in the use of a model atmosphere to provide cali-

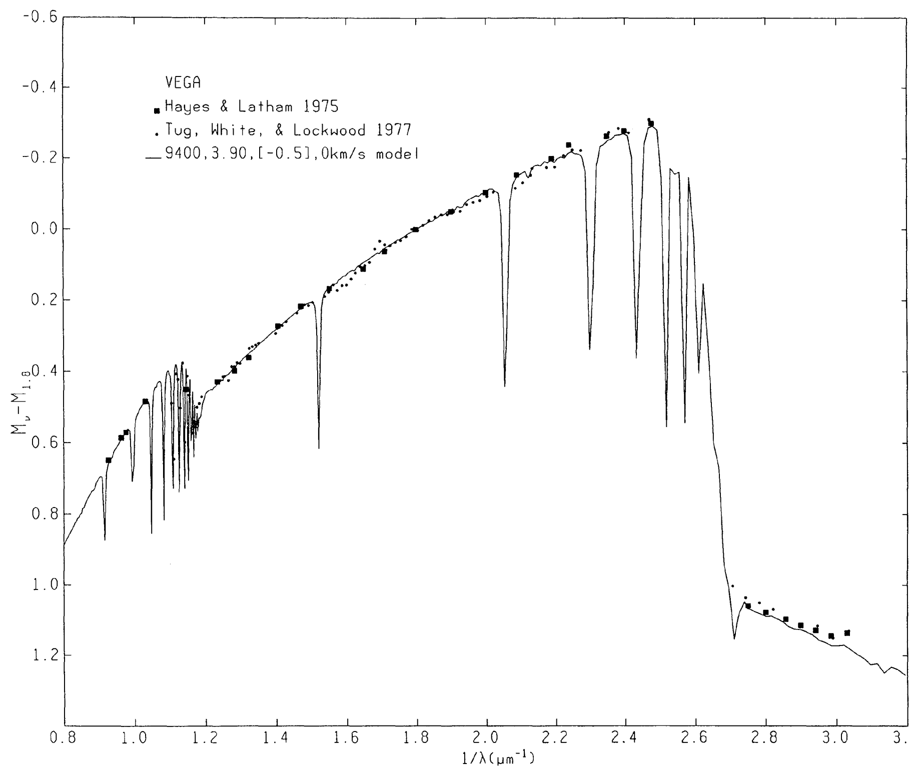

FIG. 1. Kurucz's (1991a) new model for Vega compared with a series of independent UV-optical measurements, specifically those by Hayes & Latham (1985) and by Tug *et al.* (1977).

bration and, for our purposes, continuous wavelength interpolation between the few photometric points available. However, we diverge from their approach in that we base our own calibration scheme on new models by Kurucz (1991a), as yet unpublished, that are briefly described in Sec. 2.

Deacon (1991) and Deacon *et al.* (1992a) have recently tabulated a set of magnitudes for potential infrared calibration standards that come from critical examination of the literature of ground-based measurements. They have also compared (Deacon 1991; Deacon *et al.* 1992b: hereafter DBC) the sensitivity of derived in-band fluxes for Vega to choice of model for that star (e.g., Kurucz 1979; Dreiling & Bell 1980; Kurucz 1991a). The transmission profiles of actual (UKIRT) filters at 77 K that we use are adopted from those within Deacon's dissertation. However, in the present paper we consider only the newest Kurucz models because (1) he himself has tailored the metallicities incorporated into them; (2) he has provided a customized finely-gridded wavelength scale that is suitable for infrared applications; and (3) these models contain much more physics than his 1979 set (for a full description of the physics included see Kurucz 1991b). A further divergence from DBC is that we offer here a more detailed series of comparisons between our own calibration and the original one used by *IRAS*.

2. THE NEW SPECTRA OF VEGA AND SIRIUS

Both these A dwarf stars are sufficiently hot that molecules could not survive in their atmospheres and both have been modeled in the past (Kurucz 1979; Dreiling & Bell 1980; Bell & Dreiling 1981). What distinguishes our latest Kurucz (1991a) models from all previous efforts are the metallicities inherent in Kurucz's new work. After critical examination of detailed high-resolution ultraviolet and visible spectra of Vega, Kurucz finds definite support for the idea that Vega has less than solar metallicity. Sirius, because of mass transfer from its companion, is metal-rich compared with the sun (Latham 1970). It is the presence of dust around Vega and the greater brightness of Sirius that renders the latter a more desirable standard for infrared work. Consequently, we have chosen to work with both Vega—the canonical standard at UV-optical wavelengths—and Sirius.

By strong contrast with the arbitrary adoption of blackbodies, Fig. 1 offers Kurucz's new Vega model in comparison with the UV-optical spectral energy distributions defined from a variety of narrowband observations. It is important to keep the quality of this match firmly in mind when listening to arguments for and against blackbodies as calibration models. Blackbodies do not and cannot represent real stars across the entire ultraviolet, visible, and infrared. The model offered, however, derives its credibility

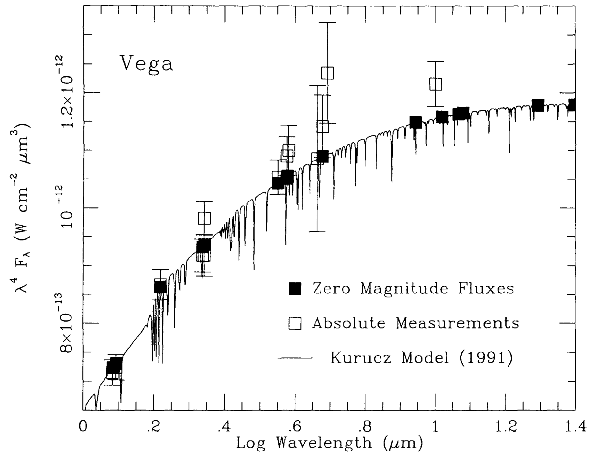

FIG. 2. The new Vega model displayed in the infrared after normalization to the Hayes (1985) average 5556 A monochromatic flux density. Solid squares represent the monochromatic flux densities obtained after integrating this model over the combined atmospheric and filter transmission profiles. Open squares with error bars denote the absolute mountaintop measurements of Vega cited in the text.

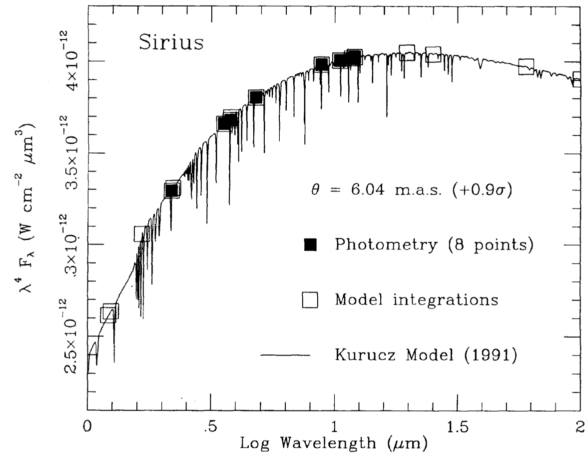

FIG. 3. Kurucz's (1991a) new Sirius model after final normalization. Open squares show actual monochromatic flux densities after integration over this model. Solid squares display the expected flux densities based on the eight magnitude differences between Vega and Sirius noted in the text, and the photometric calibration presented in Table 1(a). The implied angular diameter for Sirius is indicated on the plot along with its value relative to that measured by Hanbury Brown *et al.* (1974), in units of the σ of these authors' determination.

from the excellent reproduction of all these measurements of Vega's energy distribution (and of the Balmer line intensities and profiles). To accept an extrapolation of this model from the difficult and challenging UV-visible realm into the infrared, where lines are more widely separated, molecules negligible, and opacities are better understood than for cool stars, does not require any astrophysical compromise. The new model for Sirius (Kurucz 1991) similarly represents its UV-optical measurements.

Figure 2 presents Vega again, now in the form of a plot of $\lambda^4 F_\lambda$ (so that long and short wavelengths may be conveniently examined with equal ease in a single plot). One can independently validate the shape of this spectrum in the optical by comparison with the energy distribution for Vega tabulated by Hayes (1985: his Table II). Kurucz's new model agrees very well with the colors implied by Hayes' table. To place the model on an absolute footing we have interpolated the wavelength grid to obtain the monochromatic flux density at the astronomical standard wavelength of 5556A, then set this equal to Hayes' (1985) critically evaluated average of six independent measurements made by different groups: [$3.44 \pm 0.05 \times 10^{-9}$ erg cm^{-2} s^{-1} A^{-1}]. The filled black squares represent the results of combining both the atmospheric transmission (from a good astronomical site like Mauna Kea) and specific detailed broadband filter transmission profiles (measured at 77 K, their operating temperature: cf. DBC) with the Vega spectrum. Following Deacon, we adopt Vega as zero magnitude at all infrared wavelengths longwards of 1 μm but do not advocate use of real measurements of this star beyond ~ 20 μm for calibration purposes because of the existence of its shell of cold dust grains that first becomes apparent at about this wavelength. Consequently, the solid squares define our system of broadband "zero magnitude fluxes" (plotted with use of isophotal wavelengths: see Sec. 3). However, we do use integrations through the combination of filter and atmospheric transmission profiles over our ideal representation for Vega, namely the new model, to establish what zero magnitude should truly correspond to, even at the longest wavelengths where the real Vega has grossly departed from this ideal.

Figure 3 likewise shows the infrared portion of Kurucz's (1991a) independent model for Sirius. In this figure, open squares represent actual integrations of the stellar spectrum through the atmosphere and relevant filters. We have tested the shape of this Kurucz model in the optical against the colors provided by Davis & Webb (1974): it compares very favorably with their relative energy distribution. Initially we normalized the Sirius model in accordance with the optical interferometric angular diameter measured by Hanbury Brown *et al.* (1974) of 5.89 ± 0.16 milli-arcsec. We compared the ratios of in-band fluxes, between the calibrated Vega spectrum and the Sirius spectrum with this nominal normalization, with the factors corresponding to eight, equally weighted, expected magnitude differences {at K, L, L', M, [8.7], [10], [11.7], and [12], where [λ] denotes a magnitude at λ μm, and where we took these magnitude differences from Deacon (1991): $K = L = L' = M = -1.36$; $[8.7] = N = [11.7] = [12] = -1.35$}. We then adjusted the angular diameter of Sirius to bring the observed and expected in-band flux ratios most closely together. This required a further rescaling of the model spectrum by a factor of 1.052 ± 0.002, corresponding to an angular diameter of 6.04 mas. Solid squares in Fig. 3 are derived from the flux densities expected for these magnitude differences (flux ratios) relative to Vega, using the broadband flux calibration illustrated in Fig. 2 and given in Table 1(a).

The two Kurucz models correspond to the following parameters. For Vega: $T_{\rm eff} = 9400$ K; $\log g = 3.90$;

TABLE 1. Monochromatic fluxes for the Vega and Sirius models that define our zero magnitude system.

(a) Vega

Ground-based, narrowband set (Selby *et al.* 1988) with InSb response included at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
Jn	1.243	3.059*E*−13	1575.3
Kn	2.208	3.940*E*−14	640.1
Ln	3.781	5.162*E*−15	246.0

Ground-based, usual set (e.g., UKIRT filters) with InSb response included at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
J	1.215	3.314*E*−13	1631.0
H	1.654	1.151*E*−13	1049.7
K	2.179	4.139*E*−14	655.0
L	3.547	6.590*E*−15	276.4
L'	3.761	5.263*E*−15	248.1
M	4.769	2.107*E*−15	159.7

Ground-based, usual set (e.g., UKIRT filters) at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
8.7	8.756	1.955*E*−16	49.98
N	10.472	9.631*E*−17	35.21
11.7	11.653	6.308*E*−17	28.56
20	20.130	7.182*E*−18	9.70

IRAS bands

		Noncolor-corrected		Color-corrected	
IRAS filter	In-band flux (W cm^{-2})	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
12	5.411*E*−16	8.363*E*−17	40.141	5.616*E*−17	26.966
25	4.585*E*−17	4.265*E*−18	8.886	3.018*E*−18	6.288
60	3.732*E*−18	1.206*E*−19	1.447	9.051*E*−20	1.085
100	4.212*E*−19	1.264*E*−20	0.421	1.159*E*−20	0.386

(b) Sirius

Ground-based, narrowband set (Selby *et al.* 1988) with InSb response included at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	Mag
Jn	1.243	1.105*E*−12	5688.3	−1.39
Kn	2.208	1.392*E*−13	2262.1	−1.37
Ln	3.781	1.806*E*−14	860.9	−1.36

Ground-based, usual set (e.g., UKIRT filters) with InSb response included at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	Mag
J	1.215	1.198*E*−12	5896.4	−1.39
H	1.653	4.099*E*−13	3730.6	−1.40
K	2.179	1.463*E*−13	2315.2	−1.37
L	3.550	2.304*E*−14	967.8	−1.36
L'	3.759	1.843*E*−14	868.4	−1.36
M	4.770	7.350*E*−15	557.5	−1.36

Ground-based, usual set (e.g., UKIRT filters) at Mauna Kea

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	Mag
8.7	8.758	6.776*E*−16	173.2	−1.35
N	10.472	3.332*E*−16	121.8	−1.35
11.7	11.655	2.178*E*−16	98.62	−1.35
20	20.132	2.466*E*−17	35.31	−1.34

IRAS bands

		Noncolor-corrected		Color-corrected		
IRAS filter	In-band flux (W cm^{-2})	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)	Mag
12	1.872*E*−15	2.894*E*−16	138.895	1.941*E*−16	93.159	−1.35
25	1.572*E*−16	1.463*E*−17	30.471	1.034*E*−17	21.542	−1.34
60	1.267*E*−17	4.093*E*−19	4.911	3.066*E*−19	3.679	−1.33
100	1.421*E*−18	4.262*E*−20	1.421	3.906*E*−20	1.302	−1.32

[Fe/H] = −0.5; $v_{\rm microturb}=0$ km s^{-1}. After scaling to the Hayes' 5556 A flux density, the resulting angular diameter is 3.335 mas. The optical angular diameter measured interferometrically by Hanbury Brown *et al.* (1974) for Vega is 3.24±0.07 mas [at 1 μm Leggett *et al.* (1986) obtained 3.25±0.16]. For Sirius corresponding numbers are: 9850 K, 4.25, +0.5, 0 km s^{-1}, and 6.04 mas. Our angular diameter is only 0.9σ above the measurement by Hanbury Brown *et al.* (1974). There is an inherent absolute uncertainty in both models arising from the ±1.45% uncertainty in the Hayes (1985) 5556 A flux for Vega (cited above). The best match of the eight Sirius fluxes to independently determined broadband magnitude differences with respect to Vega introduces another source of error for Sirius, although this is very small (±0.17%: from the standard error in the mean factor given above). This increases the absolute uncertainty inherent in the Sirius spectrum from ±1.45% to ±1.46% (by root sum square combination of these two independent sources of error).

Therefore, these two models, with their current scales, represent our best estimates for absolutely calibrated continuous spectra, from which to determine broad and narrowband stellar flux densities.

3. THE ZERO MAGNITUDE FLUX CALIBRATION

After combining atmosphere and filter profiles and integrating over the two models we obtained a set of in-band fluxes for Vega. In Table 1(a) we present the equivalent monochromatic flux densities (which we define to correspond to zero magnitude) together with the accompanying "isophotal" wavelengths. The choice of isophotal as opposed to effective wavelengths is dictated by our applications to the very broad filters that typify mid-infrared astronomy. We follow the discussion of, rationale for, and definition of isophotal wavelength introduced by Brill (1938), addressed by Stock & Williams (1962), and most clearly explained by Golay (1974). Integration of our calibrated versions of the Kurucz models over a specific filter and atmospheric profile yields an appropriately weighted monochromatic flux density (in units of W cm^{-2} μm^{-1}). Conversion into Jy is achieved using the standard relation between F_ν and F_λ involving the wavelength, here taken to be the isophotal wavelength. For the *IRAS* bands we use nominal wavelengths (12, 25, 60, 100 μm), compute the in-band fluxes, and convert directly into F_ν using the standard bandpasses for these filters. F_λ calibrations again follow from the standard relation: $F_\lambda = 3.0E-16{*}F_\nu/\lambda^2$.

Table 1 includes standard ground-based filters and the three very narrow bands used by Selby *et al.* (1988) that support the determinations of angular diameter and effective temperature for 114 stars most recently applied by Blackwell *et al.* (1991) using the Infrared Flux Method. Isophotal wavelengths tabulated are determined by detailed comparison of the actual monochromatic spectral flux densities of the model with the computed monochromatic flux densities. For cool stars these wavelengths will be slightly different from those in Table 1. Table 1 also presents our calibrations for the four *IRAS* bands, in the form of in-band flux, noncolor-corrected flux densities (both F_λ and F_ν), and finally the color-corrected flux densities.

Our primary applications of these zero magnitude calibrations are to the creation of absolutely calibrated cool stellar spectra (cf. CWW). Consequently, the relevant stars are the canonical cool stellar "calibrators" of infrared astronomy. These are all very bright objects in broadband terms and their magnitudes reflect measurements made over the past two decades, largely with bolometers. However, we have also included the wavelength variations of detector quantum efficiency that characterize typical modern InSb detectors (cf. The Infrared Handbook 1978). In practice, this makes very little difference to our calculated numbers: inclusion of the quantum efficiency affects λ_{iso} by $\sim$0.005 μm, and F_λ or F_ν by $<1\%$ over the 1–5 μm region.

Table 1 formally includes the terrestrial atmosphere above Mauna Kea in the determination of isophotal wavelengths and monochromatic flux densities. However, we have also investigated those differences that arise when observing from lower elevation sites and at higher latitudes. We took Kitt Peak to be a representative example of these popular lower elevation sites.

The atmospheric transmittances that we use to represent conditions at Mauna Kea were based initially upon applications of the following: (i) the IRTRANS code (Traub & Stier 1976) by Dr. C. M. Mountain for the 1–6 μm range under the following circumstances: 1.2 mm of precipitable water vapor; an airmass of 1.00; a wavelength gridding of 0.0005 μm with Gaussian convolution to achieve a FWHM of 0.0025 μm; and appropriate values for molecular abundances and partial pressures of H_2O, CO_2, O_3, N_2O, CO, CH_4, and O_2; and (ii) the 6–14 μm atmospheric profile computed by Kyle & Goldman (1975). More recently, we have utilized a complete set of consistent atmospheric calculations based upon a CRAY YMP code ("NWATR") in use at NASA-Ames and derived from the FASCOD2 software. Lord (1992) provides a comparison of the various codes at NASA-Ames that currently all utilize the newest (1991) release of the original HITRAN database (Rothman *et al.* 1987). We used these calculations (carried out for us by J. Simpson) to represent the atmospheres at Mauna Kea and a typical lower elevation site. We find no essential differences between the results yielded by these two approaches but we prefer the homogeneous set of finely gridded models calculated with NWATR at NASA-Ames.

For this direct comparison of sites, we matched Mountain's calculations for Mauna Kea, then computed a similar model for the lower elevation, using 5.0 mm of precipitable water vapor, unit airmass, and fine wavelength gridding. Specific relevant details of the primary molecular constituents in these calculations are as follows: for Mauna Kea, $w(H_2O) = 0.418E22$, $w(CO_2) = 0.478E22$, $w(O_3) = 0.693E19$, $w(N_2O) = 0.650E19$, $w(CO) = 0.302E19$, $w(CH_4) = 0.195E20$, $w(O_2) = 0.272E25$ mol cm^{-2}; for Kitt Peak, $w(H_2O) = 0.167E23$, $w(CO_2) = 0.551E22$, $w(O_3) = 0.752E19$, $w(N_2O) = 0.837E19$, $w(CO) = 0.389E19$, $w(CH_4) = 0.251E20$, $w(O_2) = 0.350E25$ mol cm^{-2}.

The effects on isophotal wavelengths are generally very small, typically <0.005 μm, although some filters obviously sample poorer "windows" and suffer greater changes. The greatest change is for Q whose λ_{iso} goes from 20.13 μm at Mauna Kea to only 19.58 μm at Kitt Peak. This emphasizes the critical importance of defining a narrower 20 μm band that is blocked at long wavelengths rather than permitting the time-variable atmosphere to dictate both wavelength and observed in-band flux (cf. Young & Milone 1992). For no other filter does λ_{iso} alter by >0.01 μm. This change of site affects the monochromatic flux densities by much less than 1% for all filters except *Q*, where the great change in λ_{iso} clearly has consequences for the flux density. But it is far preferable to pursue *Q* photometry only from sites such as Mauna Kea where the *Q* magnitudes used by CWW of this series were obtained. For practical purposes, we also present this lower elevation calibration (including the effects of InSb wavelength-dependent quantum efficiency) as Table 2, but for Vega alone (i.e., the zero magnitude system).

In order to cope with the photometric calibration of the Strecker *et al.* (1979) spectral database (used by CWW) obtained from high altitude airborne observatories, we have also calibrated all near-infrared filters for altitudes appropriate to airborne observatories. Here the maximal effects occur for the *M* band whose λ_{iso} diminishes by 0.10 μm (to 4.665 μm) and whose flux density increases $\sim$5%. More typically, however, λ_{iso} changes by <0.02 μm, and flux densities alter by $\sim$2%.

Table 1(b) likewise includes isophotal wavelengths and monochromatic flux densities for Sirius, and its magnitudes relative to Vega = 0.0.

In Fig. 2, open squares show the best mountaintop ab-

TABLE 2. Monochromatic fluxes for the Vega model that define our zero magnitude system at lower elevation sites (e.g., Kitt Peak).

Ground-based, narrowband set (Selby *et al.* 1988) with InSb response included

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
Jn	1.243	3.059*E*−13	1575.2
Kn	2.208	3.940*E*−14	640.1
Ln	3.781	5.162*E*−15	246.0

Ground-based, usual set (e.g., UKIRT filters) with InSb response included

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
J	1.212	3.341*E*−13	1636.6
H	1.654	1.151*E*−13	1049.5
K	2.182	4.116*E*−14	653.2
L	3.561	6.497*E*−15	274.6
L'	3.751	5.315*E*−15	249.2
M	4.773	2.100*E*−15	159.5

Ground-based, usual set (e.g., UKIRT filters)

Filter name	λ_{iso} (μm)	F_λ (W cm^{-2} μm^{-1})	F_ν (Jy)
8.7	8.765	1.948*E*−16	49.88
N	10.468	9.648*E*−17	35.24
11.7	11.651	6.314*E*−17	28.57
20	19.575	8.026*E*−18	10.25

solute measures of Vega's fluxes (Blackwell *et al.* 1983; Campins *et al.* 1985; Selby *et al.* 1983; Mountain *et al.* 1985; Rieke *et al.* 1985) currently available along with their uncertainties (probably underestimated as between 3% and 10%, increasing with wavelength). To plot the points in this figure we note that some of the measurements were made with spectrometers to isolate carefully chosen "clean" portions of the earth's atmospheric windows: their declared wavelengths were used without modification (e.g., Blackwell *et al.* 1983; Mountain *et al.* 1985). However, the work of Campins *et al.* (1985) refers to the "standard Johnson" system of JHKLM bands: these are broad filters, not selected with detailed consideration of the telluric transmittance, so we chose to plot them in Fig. 2 at their actual isophotal wavelengths for the filter and atmosphere above the Catalina Mts. where the data were obtained. Note that none of these absolute determinations deviates from our calibrated Kurucz model of Vega by more than 2σ.

In spite of this proximity, the disposition of the mountaintop measurements is predominantly above the model. Therefore, it is pertinent to ask whether there is any evidence for a near- or mid-infrared analogue of the known far-infrared excess emission in Vega that could elevate these measurements above the model flux densities. Direct comparison of the *IRAS* Low Resolution spectrum of Vega (after recalibration: see CWW) with our calibrated Kurucz model of the same star indicates that no significant departures from the model are seen shortward of 16.5 μm. Consequently, at least between 7.7 and 16.5 μm and at the few percent level, no departures from the theoretical expectation occur in the real Vega. At present, one cannot definitively exclude some low level of contamination of the observed 1–5 μm energy distribution of Vega by hotter dust grains than those first detected by *IRAS*. However, we note that Bessell & Brett (1988) concluded that the apparent near-infrared excess of Vega, measured from mountaintops, was not real from their own study of the colors of other A0 stars.

Hanner & Tokunaga (1991) present their suggested Vega fluxes in a number of infrared wavebands, apparently based upon these absolute measurements rather than on any stellar model. For the five near-infrared filters in common with our own tabulations (*HKLL'M*) the average ratio of our absolute Vega flux densities to theirs is 0.98 ±0.01, consistent with these authors' reliance on the mountaintop data, which slightly exceed our Kurucz model (Fig. 2). At long wavelengths, Hanner & Tokunaga (1991) adopt "reference wavelengths" different from our isophotal wavelengths for *N* and *Q*. If we treat their wavelengths as isophotal, and extract the flux densities from our Vega model corresponding to 10.10 and 20.00 μm, our flux densities are 0.95 and 1.03 of theirs. We conclude that, within the uncertainties estimated by Hanner & Tokunaga (1991), our calibrated Vega model provides an acceptable set of zero magnitude flux densities. Furthermore, it is essential to utilize such a model in order to obtain wavelength interpolation between the scarce absolute mountaintop data points and hence cope with wavebands that are either unobservable from the ground or simply do not match the filters used in these absolute determinations.

4. THE POINT SOURCE CALIBRATION OF *IRAS*

The issue of the *IRAS* point source calibration is clearly of interest given the wealth of data provided by that satellite. A very careful reading of the *IRAS* Explanatory Supplement (1988: pg. VI-19ff) leads to the conclusion that, until we have studied every star in their Table VI.C.3, we cannot definitely address the *IRAS* point source calibration. However, several comparisons are possible, as described below.

4.1 Comparison with the IRAS Point Source Catalog Version 2 (PSC)

The most direct comparison is with the PSC because this tabulates flux densities in Jy without color-correction. These quantities are readily derived by integration of a given spectrum over the *IRAS* bandpasses and subsequent conversion of the resulting in-band fluxes to monochromatic flux densities using the *IRAS* standard filter bandwidths (*IRAS* Supplement 1988, pg. X-13). In what follows we define $R(\lambda)$ to be the ratio of one of our own flux densities at λ μm to that obtained by *IRAS*. At 12 μm on Vega the PSC gives 41.56±1.66 Jy (using both the flux density and the quantity "RELUNC" that indicates the relative uncertainty in % of a PSC measurement). Table

1(a) indicates 40.14 Jy, suggesting that $R(12)=0.966 \pm 0.039$. Likewise, for Sirius we obtain $R(12)=0.971 \pm 0.029$ (the PSC indicates $S_\nu = 143.1 \pm 4.29$ Jy). (These ratios also appear in Table 3.) At 25 μm we cannot use Vega because of its dust shell. Only Sirius can be used to compare Table 1(b) (30.47 Jy) with the PSC (33.97 ± 1.70 Jy using the 5% figure given for "RELUNC" at this wavelength). This indicates a factor, $R(25)$, of 0.899 ± 0.045. At 60 μm we again cannot use Vega, but Sirius data are still valid. Comparing Table 1(b) (4.911 Jy) with the PSC (4.92 ± 0.39 Jy using the 8% figure given for "RELUNC" at 60 μm) indicates $R(60)=0.998 \pm 0.080$. At 100 μm Vega's dust shell precludes a direct comparison with the Kurucz model and Sirius is contaminated by cirrus, so we cannot evaluate the accuracy of the *IRAS* point source calibration at this longest wavelength using stellar measures.

4.2 Comparison with the IRAS Explanatory Supplement's Subset of Stars

The *IRAS* Explanatory Supplement (1988) places great reliance on developing the *IRAS* point source calibration on the basis of a set of eight stars (Table VI.C.3) which were measured by specific pointed observations. In this special calibration mode of *IRAS*, stars of interest were scanned across optimal "photometric tracks" in the focal plane during the survey (i.e., through the best characterized detectors). These observations had smaller intrinsic dispersion than the normal survey observations. Indeed, Aumann *et al.* (1984) felt this method offered the most accurate data from *IRAS* on such stars and they quote probable errors of 1%, 2.5%, 2%, and 3% at 12, 25, 60, 100 μm for such flux densities. The Supplement does not offer any information on uncertainties for specific stellar magnitudes cited in Table VI.C.3 so we adopt the probable errors cited by Aumann *et al.* We, therefore, directly compare these most accurate *IRAS* flux densities of Vega (whose 12 μm mag, although not stated, is +0.01 within the context of Table VI.C.3) and Sirius with our own calibrated spectra of these stars. Table VI.C.3 implies 28.04 (Vega) and 99.03 Jy (Sirius) at 12 μm, and 22.70 Jy (Sirius alone) at 25 μm. The Supplement states that all these flux densities have been color-corrected treating each star as "a hot blackbody." We, therefore, assume that the color-correction factors given in Table VI.C.6 of the Supplement were applied, namely 1.45 at 12 μm, and 1.41 at 25 μm (corresponding to a roughly 10 000 K blackbody). Therefore, we deduce that the noncolor-corrected fluxes (the style given in the PSC) were 40.65 Jy (Vega at 12 μm) and 143.6 and 32.01 Jy (Sirius at 12 and 25 μm, respectively) which are to be compared with our own numbers of 40.14, 138.9, and 30.47 Jy, respectively. These comparisons suggest $R(12)=0.987$ (Vega) and 0.967 (Sirius), each with uncertainty of ± 0.01, and $R(25)=0.952 \pm 0.025$ (Sirius).

TABLE 3. Ratios of our calibration stellar fluxes to those measured by *IRAS*.

Star	Wavelength	$R(\lambda)$	Uncertainty	Comparison with
Vega	12	0.966	0.039	PSC
		0.987	0.01	Table VI.C.3
Sirius	12	0.971	0.029	PSC
		0.967	0.01	Table VI.C.3
Combined	12	0.976	0.007	4 values above
Zero mag	12	0.978		
Sirius	25	0.899	0.045	PSC
		0.952	0.025	Table VI.C.3
Combined	25	0.940	0.022	2 values above
Zero mag	25	0.936		
Sirius	60	0.998	0.08	PSC
		0.971	0.02	Table VI.C.3
Combined	60	0.973	0.019	2 values above
Zero mag	60	0.921		
Zero mag	100	0.896		

4.3 Combined Results and Comparison of Zero Point Flux Densities

Table 3 summarizes these several sets of stellar comparisons and presents their combinations, for different wavelengths, using inverse variance weighting.

The three separate determinations (or adoptions) of Vega's [12] by *IRAS* [-0.02 ± 0.06 (survey, mistyped in the Explanatory Supplement on page VI-21 as 0.02), $+0.01 \pm 0.01$ (pointed observations), and -0.01 ± 0.01 (Aumann *et al.* 1984)] are all consistent with our own system in which the Vega model is taken to define zero magnitude at all wavelengths. Consequently, it is meaningful to compare our own zero mag flux densities directly with those adopted by *IRAS*. After removing the color corrections stated to have been made by *IRAS* (1.45, 1.41, 1.32, 1.09 from Table VI.C.6), we deduce the *IRAS* quartet of noncolor-corrected flux densities for zero mag to be (41.04, 9.49, 1.57, 0.47 Jy). Our own values are (40.141, 8.886, 1.447, 0.421 Jy) which yields $R(12, 25, 60, 100)=(0.978, 0.936, 0.921, 0.896)$.

Although incomplete by comparison with the actual process pursued by the *IRAS* Science Team, these figures suggest that the current *IRAS* absolute calibration is too high by 2.4%, 6.5%, 2.9%, and 11.6% in the four wavebands, respectively. These estimates could surely be improved by a more rigorous explanation of, and duplication of, the procedures actually carried out in the calibration of *IRAS*.

5. CONCLUSIONS

We have presented absolutely calibrated versions of realistic model atmosphere calculations by Kurucz for Vega and Sirius on the basis of which we offer a new absolute calibration of infrared broad and narrow filters, and make a preliminary comparison with the current *IRAS* point source calibration. One could explore the influence on these wavelengths and flux densities of varying the site in question with respect to latitude, longitude, season, even to those profound variations on water vapor (by up to a factor of 10) that can characterize night conditions in some locations. All these circumstances affect λ_{iso} and F_λ for zero mag. However, at this point we feel that equally large changes (if not larger ones) can result from variations in allegedly "standard infrared filters" from observatory to observatory (cf. 2.2.2 of Hanner & Tokunaga 1991), particularly given the past reluctance of most sites to publish cold scans of their filter profiles.

We advocate the use of Sirius as a primary infrared stellar standard; encourage the publication of the corresponding magnitudes of Vega (below 20 μm) and of Sirius whenever new infrared photometric filter systems and standards are developed; and urge the adoption of truly "standard" infrared filters whose transmission profiles, obtained at their actual operating temperatures, have also been published for integration over calibrated stellar models such as the ones we offer here for Vega and Sirius. We note that Young & Milone (1992) argue cogently for a new infrared system of filters that would minimize the variations of λ_{iso} with altitude of observing site.

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REFERENCES

Aumann, G., *et al.* 1984, ApJ, 278, L23
Bell, R. A., & Dreiling, L. A. 1981, ApJ, 248, 1031
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Blackwell, D. E., Leggett, S. K., Petford, A. D., Mountain, C. M., & Selby, M. J. 1983, MNRAS, 205, 897
Blackwell, D. E., Booth, A. J., Petford, A. D., Leggett, S. K., Mountain, C. M., & Selby, M. J. 1986, MNRAS, 221, 427
Blackwell, D. E., Petford, A. D., Arribas, S., Haddock, D. J., & Selby, M. J. 1990, A&A, 232, 396
Blackwell, D. E., Lynas-Gray, A. E., & Petford, A. D. 1991, A&A, 245, 567
Brill, A. 1938, Zs. f. Astrophys., 15, 137
Campins, H., Rieke, G. H., & Lebofsky, M. J. 1985, AJ, 90, 896
Cohen, M., Walker, R. G., & Witteborn, F. C. 1992, AJ (in press) (CWW)
Cohen, M., Witteborn, F. C., Carbon, D., Augason, G., Wooden, D., Bregman, J., & Goorvitch, D. 1992, AJ (in press)
Davis, J. & Webb, R. J. 1974, MNRAS, 168, 163
Deacon, J. R. 1991, Ph.D. dissertation, University College, London
Deacon, J. R., Barlow, M. J., & Cohen, M. 1992a, in preparation
Deacon, J. R., Barlow, M. J., & Cohen, M. 1992b, in preparation (DBC)
Dreiling, L. A., & Bell, R. A. 1980, ApJ, 241, 737
Golay, M. 1974, Introduction to Astronomical Photometry, Vol. 41 in the Astrophysics and Space Science Library (Reidel, Dordrecht), pp. 39–46
Hanbury Brown, R., Davis, J., & Allen, L. R. 1974, MNRAS, 167, 121
Hanner, M. S., & Tokunaga, A. T. 1991, in Comets in the Post-Halley Era, Vol 1., edited by R. L. Newburn *et al.* (Kluwer, Holland), p. 67
Hayes, D. S. 1985, in Calibration of Fundamental Stellar Quantities, Proc. IAU Symposium No. 111, edited by D. S. Hayes, L. E. Pasinetti, and A. G. Davis Philip (Reidel, Dordrecht), p. 225
Hayes, D. S., & Latham, D. W. 1985, ApJ, 197, 593
IRAS Explanatory Supplement, 1988, IRAS Catalogs and Atlases, Volume 1, NASA RP-1190
Kurucz, R. L. 1979, ApJS, 40, 1
Kurucz, R. L. 1991a, private communication
Kurucz, R. L. 1991b, New lines, New models, New colors, in Proceedings of the workshop on "Precision Photometry: Astrophysics of the Galaxy," edited by A. G. Davis Philip, A. R. Upgren, and K. A. Janes (Davis, Schenectady), p. 27
Kyle, T. G., & Goldman, A. 1975, Atlas of Computed IR Atmospheric Absorption Spectra, NCAR-TN STR-112
Latham, D. W. 1970, Ph.D. dissertation, Harvard University
Leggett, S. K., Mountain, C. M., Selby, M. J., Blackwell, D. E., Booth, A. J., Haddock, D. J., & Petford, A. D. 1986, A&A, 159, 217
Lord, S. D. 1992, A New Software Tool for Computing the Earth's Atmospheric Transmission of Near-Infrared and Far-Infrared Radiation, NASA CR, in preparation
Mountain, C. M., Leggett, S. K., Selby, M. J., Blackwell, D. E., & Petford, A. D. 1985, A&A, 151, 399
Rieke, G. H., Lebofsky, M. J., & Low, F. J. 1985, AJ, 90, 900
Rothman, L. S., *et al.* 1987, Appl. Optics, 26, 4058
Selby, M. J., Mountain, C. M., Blackwell, D. E., Petford, A. D., & Leggett, S. K. 1983, MNRAS, 203, 795
Selby, M. J., Hepburn, I., Blackwell, D. E., Booth, A. J., Haddock, D. J., Arribas, S., Leggett, S. K., & Mountain, C. M. 1988, A&AS, 74, 127
Stock, J., & Williams, A. D. 1962, in Stars and Stellar Systems, Vol. II, Astronomical Techniques, edited by W. A. Hiltner (Univ. of Chicago Press, Chicago), p. 374
Strecker, D. W., Erickson, E. F., & Witteborn, F. C. 1979, ApJS, 41, 501
The Infrared Handbook 1978, edited by W. L. Wolfe and G. J. Zissis (US Govt. Printing Office, Washington, DC), p. 11
Traub, W. A., & Stier, M. T. 1976, Appl. Optics, 15, 364
Tug, H., White, N. M., & Lockwood, G. W. 1977, A&A, 61, 679
Young, A. T., & Milone, E. F. 1992, A&A (in press)