# Absolute Spectrally Continuous Stellar Irradiance Calibration in the Infrared

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**Abstract**

We present first efforts to establish a network of absolutely calibrated continuous infrared spectra of standard stars across the 1–35$\mu$m range in order to calibrate arbitrary broad and narrow passbands and low-resolution spectrometers from ground-based, airborne, balloon, and satellite-borne sensors. The value to photometry of such calibrated continuous spectra is that one can integrate arbitrary filters over the spectra and derive the stellar in-band flux, monochromatic flux density, and hence the magnitude, for any site. This work is based on new models of Sirius and Vega by Kurucz which were calculated by him, for the first time, with realistic stellar metallicities and a customized finely-gridded infrared wavelength scale. We have absolutely calibrated these two spectra and have calculated monochromatic flux densities for both stars, and isophotal wavelengths, for a number of infrared filters. Preliminarily, the current IRAS point source flux calibration is too high by 2, 6, 3, and 12% at 12, 25, 60, and 100$\mu$m, 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.* (1992a) have demonstrated from ratios of cool stellar spectra to that of Sirius that even early K-type stars such as $\alpha$ Boo are far from featureless blackbodies. In order to develop spectrally continuous absolute standards in the infrared, Cohen, Walker, and Witteborn (1992) have devised a technique for splicing together absolutely calibrated versions of existing spectral fragments and have demonstrated the



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method by producing a complete 1.2–35$\mu$m absolutely calibrated spectrum of $\alpha$ Tau. Their method depends in part upon correct normalization of spectral fragments in accordance with infrared stellar photometry. We summarize the independent effort on broadband infrared calibration that supports this spectral calibration scheme.

## 2. New spectra of Sirius and Vega by Kurucz

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 and Bell 1980; Bell and Dreiling 1981). What distinguishes our latest Kurucz (1991) 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.

## 3. Calibration of the new spectra

We normalize the Vega model to Hayes' 5556A weighted average monochromatic measurement, and integrate it through a variety of infrared filters using transmission profiles taken at their operating temperatures, and detailed model calculations for terrestrial atmospheric transmission. We take Vega as zero magnitude at all wavelengths up to 20$\mu$m and use existing infrared photometry differentially to scale the new Sirius model absolutely, to provide the calibration past 20$\mu$m because of Vega's dust shell. This effectively determines the angular diameter of Sirius to be 6.04 mas, well within the 1$\sigma$ uncertainty (0.16 mas) of the Hanbury Brown, Davis, and Allen (1974) measurement (5.89 mas). We hope that the stellar interferometry programme, described in Session 2 of this meeting by Shobbrook, will result in a more precise measurement of Sirius' diameter than the 1974 one. Figure 1 presents the calibrated Vega spectrum in the form of a $\lambda^4 F_\lambda$ plot and compares the model with absolute measurements attempted from mountaintops. Note that nowhere do these deviate by more than 2$\sigma$ from our calibrated model spectrum.

Using detailed terrestrial atmospheric codes supported by the 1991 release of the HITRAN database (Rothman *et al.* 1987), we calculate isophotal wavelengths and monochromatic flux densities for both stars from different ground-based sites. Details of these flux density calibrations and the calibrated hot stellar spectra appear in Cohen *et al.* (1992b).

Another application of these calibrated spectra is to the IRAS point source flux density calibration. This calibration is clearly of interest given the wealth of data provided by that satellite. Until we have constructed a detailed spectrum for every star in Table VI.C.3 of the IRAS Explanatory Supplement (1988: pg.VI-19*ff*) we cannot definitively address the IRAS point source calibration. However, direct comparisons are possible with Vega and Sirius from which Cohen *et al.* (1992b) conclude 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 be refined by a more rigorous explanation of the procedures actually carried out in the calibration of IRAS.

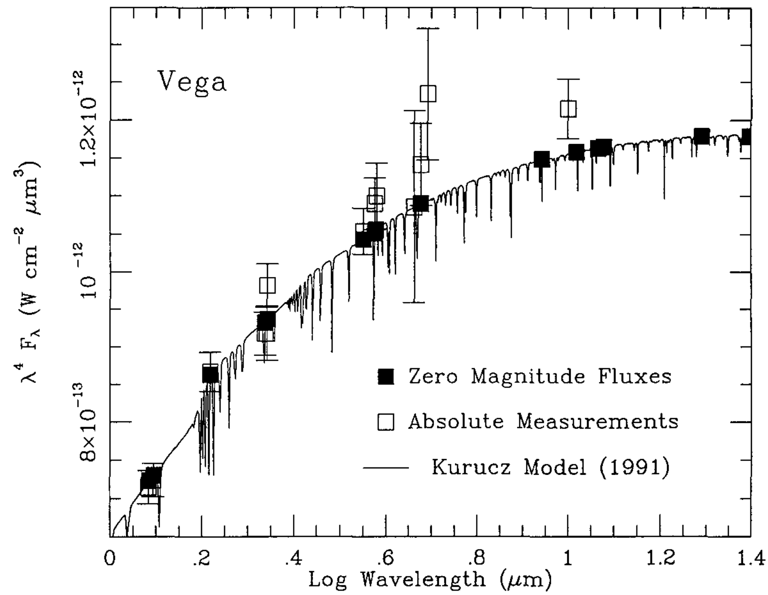


**Figure 1** The calibrated spectrum of Vega based on the new Kurucz model. Filled squares indicate our "zero magnitude flux calibrations" for the UKIRT filter set. Open squares signify absolute measurements of Vega that were attempted from mountaintops.

## 4. Construction of complete continuous calibrated spectra

Below we define the several salient procedures undergone in order to construct an absolutely calibrated infrared spectrum of a given star.

*a*) Define flux density calibrations only for filters with known cold-scanned transmission profiles using terrestrial atmospheric models based on the updated 1991 release of the "HITRAN" database.

*b*) Cull photometry with errors from the literature only if magnitudes are given for standard stars (initially only Vega and Sirius were acceptable; after constructing our own spectra of other standard stars, however, we were able to extend this acceptance to literature that designated system magnitudes for $\alpha$ Tau, $\beta$ Peg, and $\alpha$ Boo).

*c*) Locate and examine all relevant spectral fragments with known calibration pedigree (clearly, we still prefer the ratio of a star to Sirius's spectrum, when avail-

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able).

*d*) Normalize fragments with respect to photometric bands that lie wholly within the wavelength range covered by the fragments.

*e*) Single-sidedly splice one spectrum to an overlapping spectrum.

*f*) Double-sidedly splice to two flanking spectra, each overlapping the fragment.

All such splicing operations are implemented by $\chi^2$ minimization techniques over the wavelength regions common to overlapping spectral fragments. These techniques result in the best-fit rescaling of one fragment with respect to another, and generate a bias (a wavelength-independent uncertainty) from the process that is incorporated (in a root-sum-square sense) into the existing wavelength-dependent uncertainties.

Figure 2 compares the complete spectrum of $\alpha$ Tau with a simple continuum approximation with the dominant opacity source as $H^-$ free-free absorption (Engelke 1990).

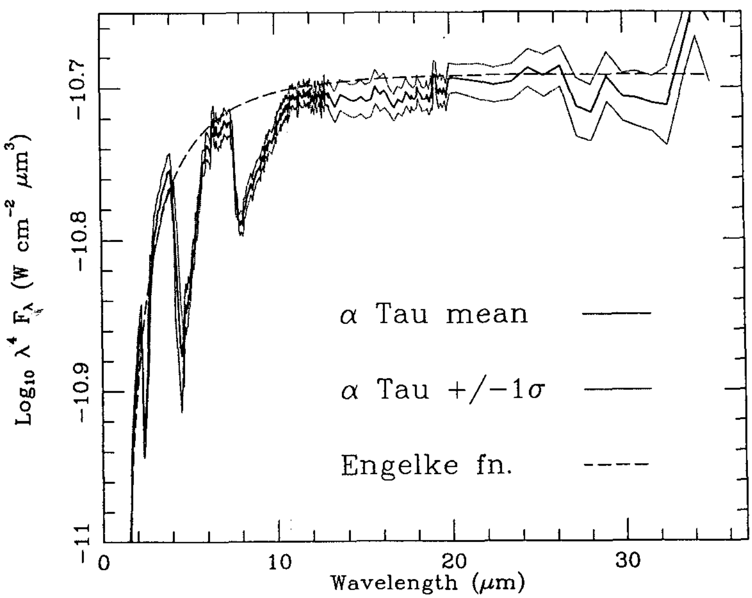


**Figure 2** The complete spectrum of $\alpha$ Tau built according to the procedures just described. Note the absorptions of CO (1st overtone), CO (fundamental), and SiO (fundamental), from left to right across the spectrum. The $1\sigma$ error bounds are plotted. These include the 1.45% uncertainty inherent in the Hayes' determination of Vega's visual flux: this component underpins all other absolute uncertainties in this method of spectral assembly.

## 5. Tables of magnitudes based on Vega and Sirius

Infrared astronomy suffers from a plethora of filters, none of them truly stan-

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dard, and an apparent reluctance on the part of observatories to publish the filter transmission profiles ***taken at their actual cryogenic operating temperature.*** Attempts have been made to relate magnitudes in these different filters to one another (e.g., see the paper by Leggett, Oswalt, and Smith in Session 1 of this meeting; Bessell

Table 1. Near-infrared magnitudes of calibration stars derived from our continuous spectra. Upper stars have calibrated Kurucz models; lower stars represent our complete, calibrated, observed spectra.

| Star | Jn | Kn | Ln | J | H | K | L | L' | M |
|---|---|---|---|---|---|---|---|---|---|
| $\alpha$ Lyr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $\alpha$ CMa | -1.39 | -1.37 | -1.36 | -1.39 | -1.40 | -1.37 | -1.36 | -1.36 | -1.36 |
| $\beta$ And | -0.89 | -1.94 | -2.06 | -0.79 | -1.74 | -1.90 | -2.03 | -2.04 | -1.78 |
| $\alpha$ Tau | -1.97 | -2.93 | -3.06 | -1.84 | -2.74 | -2.90 | -3.04 | -3.05 | -2.77 |
| $\beta$ Peg | -1.18 | -2.33 | -2.49 | -1.09 | -2.09 | -2.29 | -2.45 | -2.47 | -2.20 |
| $\alpha$ Boo | -2.27 | -3.08 | -3.17 | -2.14 | -2.96 | -3.05 | -3.16 | -3.16 | -2.91 |

Table 2. Mid-infrared magnitudes of calibration stars derived from our continuous spectra. Upper stars have calibrated Kurucz models; lower stars represent our complete, calibrated, observed spectra.

| Star | 8.7 | N | 11.7 | Q | IRAS12 | IRAS25 |
|---|---|---|---|---|---|---|
| $\alpha$ Lyr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ... |
| $\alpha$ CMa | -1.35 | -1.35 | -1.35 | -1.34 | -1.35 | -1.34 |
| $\beta$ And | -1.96 | -2.04 | -2.11 | -2.11 | -2.09 | -2.11 |
| $\alpha$ Tau | -2.95 | -3.02 | -3.07 | -3.08 | -3.08 | -3.10 |
| $\beta$ Peg | -2.37 | -2.44 | -2.49 | -2.51 | -2.48 | -2.51 |
| $\alpha$ Boo | -3.09 | -3.14 | -3.17 | -3.17 | -3.17 | -3.16 |

and Brett 1988). Young, Milone, and Stagg (Session 4, this meeting) will present an improved set of infrared passbands which it is hoped the worldwide infrared community will adopt. These new passbands have several merits, such as the ability to extrapolate more readily to zero airmass, and reduced sensitivity of isophotal wavelength on altitude of observing site. Having constructed absolutely calibrated stellar spectra based upon best-fitting pre-existing photometry, we can now invert the process and derive refined photometry for these stars by integrating the products of filter-plus-atmospheric profiles over the calibrated spectra. We present the infrared magnitudes of stars for which we have either calibrated Kurucz models, or have already constructed complete spectra. In Tables 1 and 2, we present magnitudes for the three narrowbands defined by Selby *et al.* (1988:Jn,Kn,Ln), the UKIRT filter set (JHKLL'M,[8.7],N,[11.7],Q), and IRAS (12,25). Of course, there is always still more work to be done to extend these bright standards, suitable for spectroscopy, to much fainter standards appropriate to two-dimensional infrared arrays (see the papers by Leggett *et al.* in Session 1, and by Glass in Session 3). We would be happy to provide isophotal wavelengths and corresponding magnitudes for stars using the new passbands proposed by the Working Group on IR Filters of IAU Commission 25 (see the paper by Young *et al.* in Session 4), as well as the fundamental monochromatic or in-band quantities from our calibrated Vega spectrum.

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## Discussion

**A.T. Young:** *How do you extend this calibration from $\alpha$ Tau to the whole sky?*

**Cohen:** If we assume that every K5III star looks like our absolutely calibrated $\alpha$ Tau spectrum then we can proceed as follows. Take the completely observed $\alpha$ Tau spectrum, deredden it for the known interstellar extinction and normalize the result. Now, to transfer this normalized 'template' shape to another K5III star not spectrally observed, we apply the known interstellar extinction of this other K5III star, to the intrinsic template and then fit the resulting shape to independently calibrated IR photometry of the star in question. This provides us with a first order calibrated spectrum for each K5III star across the sky with known $A_V$ and IR photometry. We have to observe, completely, one star of each type from K0-M0III then apply the template technique to tens, indeed hundreds, of stars across the sky in this spectral type range.

**E.F. Milone:** *You've discussed absolute calibration but do you want to say something further — on say the stability of the cavity?*

**Cohen:** We hope that some national laboratory will build for us and accredit, a black body furnace that we can put in a vault and compare with our current airborne cavity, both before and after a calibration flight. It's apparently quite difficult to find a lab that can accredit a Black Body across the entire 2-35 mm range - NIST(the old US 'NBS') cannot yet do this. We'll be talking to the NPL in the UK next.

**S.K. Leggett:** *First, NPL did calibrate the blackbody used by Selby et al in their calibration. Second, how does the new Kurucz model compare to the old Dreiling and Bell model for Vega that was previously used for calibration?*

**Cohen:** That old Oxford furnace has been located recently but is no longer working. We'd like NPL to design and/or build us a newer, even better one as our accredited absolute reference blackbody.

Kurucz ran about 28 different Vega models, sampling phase space (log T, log g, [He/H], microturbulent velocity) before he settled on the 9400K model for our calibration work. Roger Bell did not search phase space in the same way, nor did he examine very high resolution UV-optical spectra to validate his model. Consequently, he didn't really *determine* $T_{eff}$ in the way Kurucz did; at least that's what Roger told me last year. The Dreiling and Bell Vega model had $T\_eff$ = 9650 K, so it's hotter than our calibrated Kurucz model; consequently it falls below ours in $\lambda^4 F_\lambda$ space, and is even further below the absolute mountain top measurements.

**I.S. Glass:** *Can you comment on the alleged variablity of Vega at the 0.02 mag level?*

**Cohen:** In an infant science like IR astronomy I don't think we can comment about variations at the 2% level. Of course, we have now transferred our attention to Sirius as our primary spectral standard and it's that star that we hope to hear is non-variable.