*Astronomical Infared Spectroscopy: Future Observational Directions*
*ASP Conference Series, Vol. 41, 1993*
*Sun Kwok (ed.)*

# ABSOLUTE SPECTRALLY CONTINUOUS STELLAR IRRADIANCE CALIBRATION IN THE INFRARED

MARTIN COHEN
Radio Astronomy Laboratory, 601 Campbell Hall, University of California, Berkeley, CA 94720 and Jamieson Science & Engineering, Inc., 5321 Scotts Valley Drive, Suite 204, Scotts Valley, CA 95066

RUSSELL G. WALKER
Jamieson Science & Engineering, Inc., 5321 Scotts Valley Drive, Suite 204, Scotts Valley, CA 95066

MICHAEL J. BARLOW & JOHN R. DEACON
Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, England, UK

FRED C. WITTEBORN[1], DUANE CARBON[2] & GORDON AUGASON[3],
NASA-Ames Research Center, Moffett Field, CA 94035-1000
[1] Astrophysics Branch, Code SSA, M.S. 245-6; [2] NAS Systems Development Branch, Code RND, M.S. 258-5; [3] Space Instrumentation and Studies Branch, Code SFI, M.S. 244-B

ABSTRACT We have begun to establish a network of 1-35 μm absolutely calibrated continuous infrared spectra of standard stars to calibrate arbitrary broad and narrow passbands and ground-based, airborne, balloon, and space-borne low-resolution spectrometers. Fundamentals of CO and SiO cause substantial features from 4-12 μm and create known irregularities in broadband infrared photometry of "standard stars".

## 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...". While the broadband situation may be immature, the subject of "standard" continuously calibrated stellar spectra has been even more poorly explored. Strecker, Erickson & Witteborn (1979: hereafter SEW) published a set of calibrated 1.2-5.5 μm stellar spectra obtained from NASA's Lear Jet and Kuiper Airborne Observatories (KAO). These airborne platforms offer the vital advantage of essentially continuous spectral coverage for the brightest objects, as opposed to ground-based measurements that are constrained by the opaque regions 2.5-2.8 μm (blocked by terrestrial $H_2O$), 4.2-4.4 ($CO_2$), ~5-7.5, ~13-17, and the difficult zone from 4-5 μm (highly time-variable transmission). SEW carefully set out their rationale for absolute calibration based on Vega. In spite of these authors' considerable effort, relatively little use has been made of the SEW tabulations by observers, and no-one has ventured a comparable effort for the ground-based 8-13 μm window.

## OUR NEW APPROACH TO INFRARED CALIBRATION

Our approach is based on new models of Sirius and Vega by Kurucz and calculated by him, for the first time, with realistic stellar metallicities and a customized finely-gridded infrared wavelength scale. 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 μm and use existing infrared photometry differentially to scale the new Sirius model absolutely, to provide the calibration past 20 μm because of Vega's dust shell. We calculate monochromatic flux densities for both stars and isophotal wavelengths. Details of these flux density calibrations and the calibrated hot stellar spectra appear in Cohen et al. (1992a).

We have evolved a technique for producing high quality calibrated spectra, with quantitative uncertainties, that depends critically on three items:

1. the existence of high signal-to-noise IR spectral fragments, partially spanning the desired wavelength range, whose "calibration pedigree" is known; i.e. such fragments should derive from an archive in which spectral ratios are maintained, of the requisite stars against a small number of stars with a well-understood shape having their own absolute flux calibration (primary and secondary calibrators);

2. the existence of at least one absolutely calibrated stellar spectral standard star to provide a reference for the archive of ratioed spectra (our calibrated Vega and Sirius spectra fill this role as primary calibrators);

3. a set of independently calibrated broad and/or narrowband infrared photometric measurements on every star of interest with an established photometric calibration pedigree;

i.e. the photometry of at least one truly standard star must have been established as a reference in precisely the same filter bands.

We now define and illustrate the salient procedures undergone in order to construct an absolutely calibrated infrared spectrum of a given star, assuming that the above three requirements have been satisfied.

1. Define flux density calibrations only for filters with known transmission profiles using terrestrial atmospheric HITRAN-based models (FASCODE, NWATR, ATRAN). The latter two are newer codes that represent the terrestrial atmospheric transmission that are implemented at NASA-Ames Research Center based upon the updated 1991 release of the original Rothman et al. (1987) "HITRAN" database).
2. 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 are able to extend this acceptance to literature that designates system magnitudes for $\alpha$ Tau, $\alpha$ Boo, and $\beta$ Peg).
3. 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 available).
4. Normalize fragments with respect to photometric bands that lie wholly within the wavelength covered by the fragments (Fig. 1).
5. Splice overlapping spectra to one another when there is a single common wavelength interval (Fig. 2).
6. Splice an intervening fragment to two flanking spectra using the double-sided overlap (Fig. 3).

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.

Cohen, Walker, & Witteborn (1992) have recently detailed this method of complete spectral construction for $\alpha$ Tau. Their complete spectrum appears in Fig. 4 where it is compared with a simple approximation for the infrared continuum based on $H^-$ free-free opacity. The absolute uncertainty in this spectrum appears in Fig. 5 where it is expressed as a fraction of the flux density at every wavelength. Cohen et al. (1992b) have been able to synthesize this spectrum ab initio using a model atmosphere constructed to represent $\alpha$ Tau that incorporates only CO and SiO absorptions (beyond the continuum opacity sources). This model confirms the identity of the major absorption features in the $\alpha$ Tau spectrum.

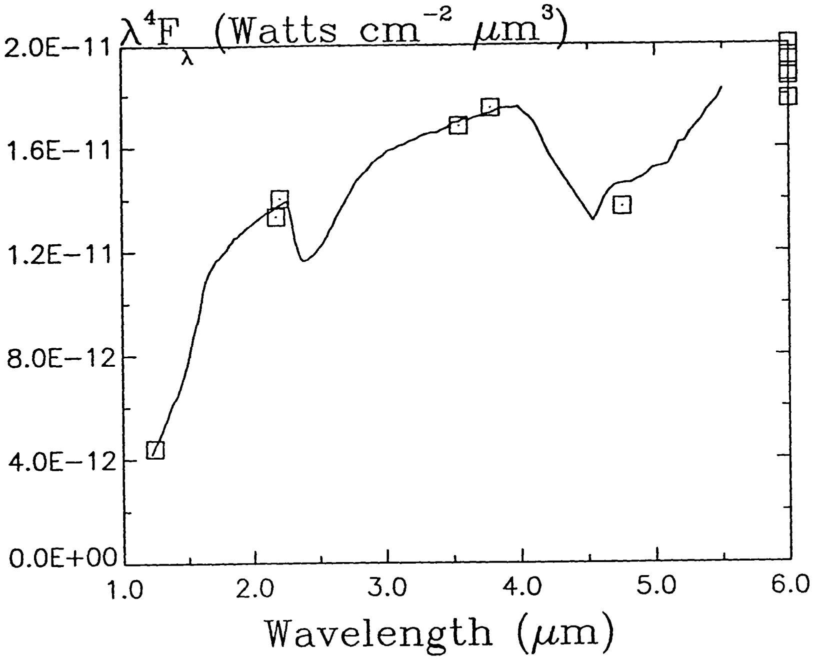

Fig. 1. Normalization of the 1.2–5.4 $\mu$m KAO spectrum of $\alpha$ Tau (solid line) with respect to calibrated broad and narrowband photometry (open squares).

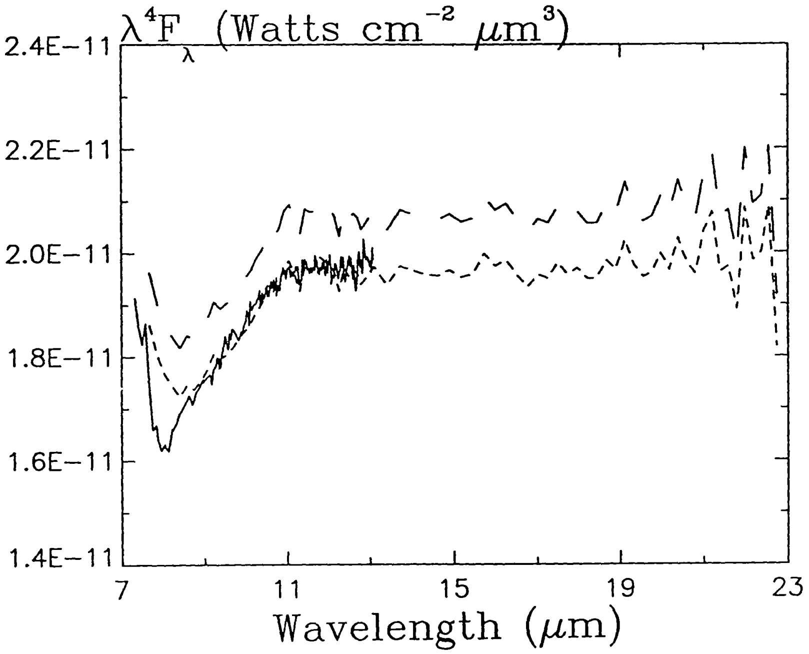

Fig. 2. Correctly-shaped LRS spectrum of $\alpha$ Tau (long dashes) spliced to ground-based 8–13 $\mu$m spectrum (solid line), suggesting the rescaled LRS (short dashes).

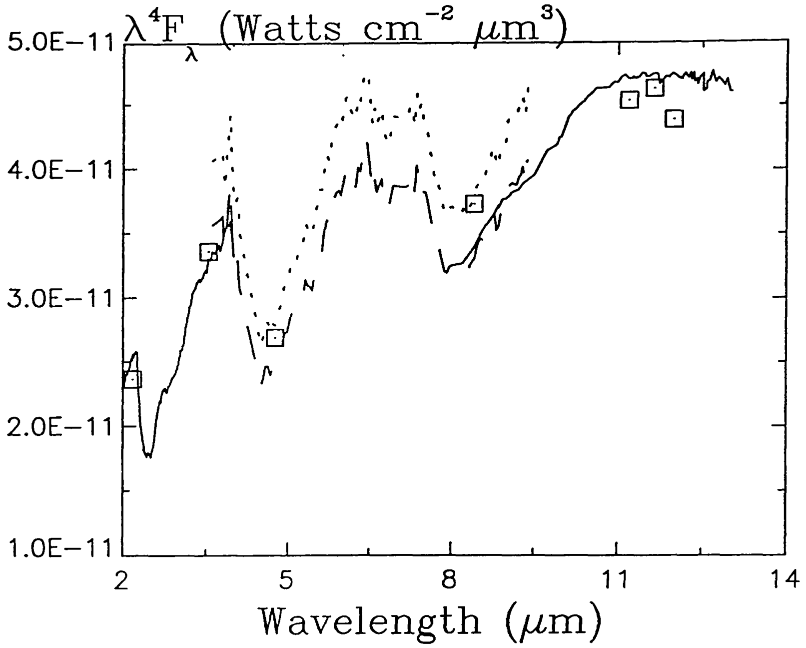

Fig. 3. Double-sided splice of 3.9–9.4 $\mu$m KAO $\alpha$ Her spectrum (short dashes) to the 1.2–4.0 $\mu$m KAO and ground-based 8–13 $\mu$m spectra (solid lines), giving long dashed rescaled KAO spectrum. Both solid lined fragments were independently normalized to photometry (open squares).

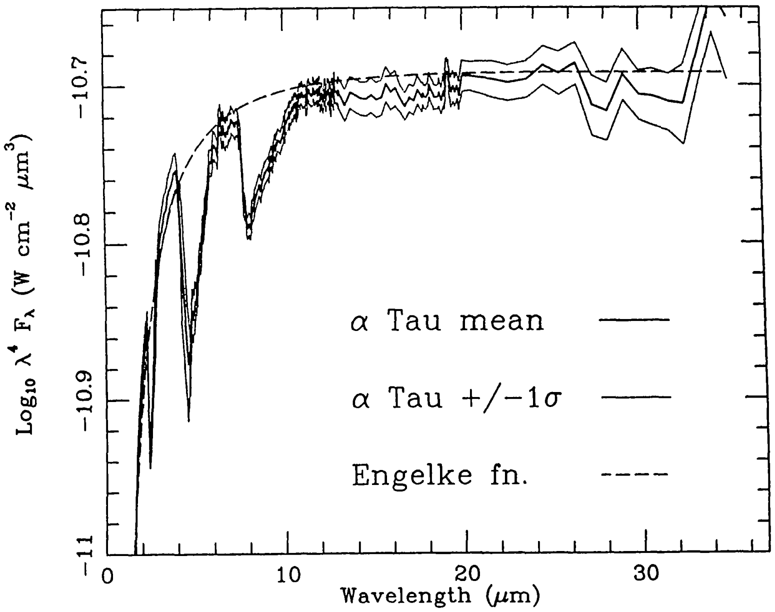

Fig. 4. The complete $\alpha$ Tau spectrum (heavy line), its $\pm1\sigma$ bounds (light continuous lines), and the $H^-$ free-free dominated approximation suggested by Engelke (1990) after suitable rescaling.

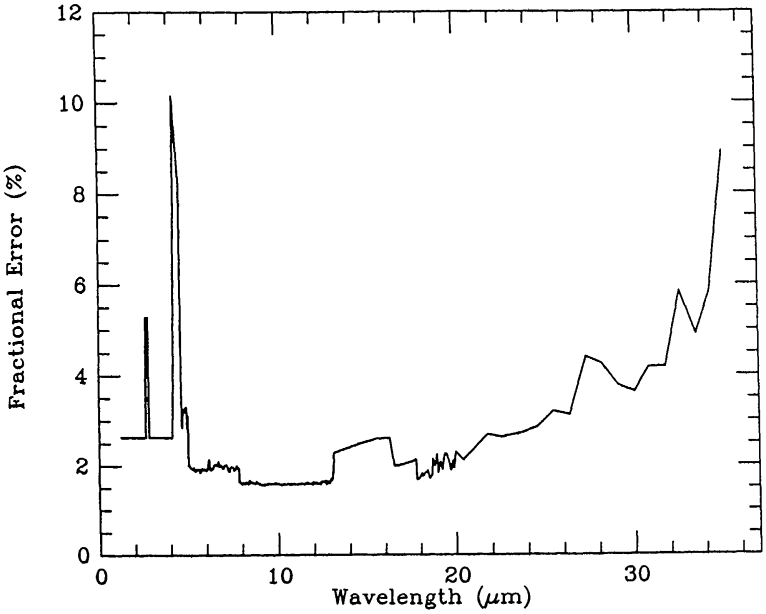

Fig. 5. Absolute uncertainty of the $\alpha$ Tau spectrum expressed as the fractional error at each wavelength in percent.

## THE IRAS LRS DATABASE

It is also clear that, in order to span the wide wavelength range required, the Infrared Astronomical Satellite Low Resolution Spectrometer [LRS] must play an important role because it alone covers the 14-16 $\mu$m region that is totally obscured by terrestrial $CO_2$, even from high-altitude observatories. The LRS, too, has a calibration originally founded on the assumption that the cool K5III star $\alpha$ Tau has a featureless infrared spectrum between 7.7 and 22.7 $\mu$m that mimics that of a 10,000K blackbody. Cohen, Walker, & Witteborn (1992) treat the "recalibration" of the LRS spectral database, based in part on their newly-assembled spectrum of $\alpha$ Tau. This "global repair" means that one can then rely on the LRS dataset to provide correctly shaped spectra for subsequent stars for which calibrated spectra are desired. The function required to fix the LRS (Fig. 6) is similar to that of Volk & Cohen (1989) but its overall shape is much more accurate than the earlier effort, especially in the red. The primary feature in Fig. 6 represents the neglect of the SiO fundamental absorption band in the $\alpha$ Tau spectrum: one divides a point-source-extracted LRS spectrum by the function in Fig. 6 to correct its shape.

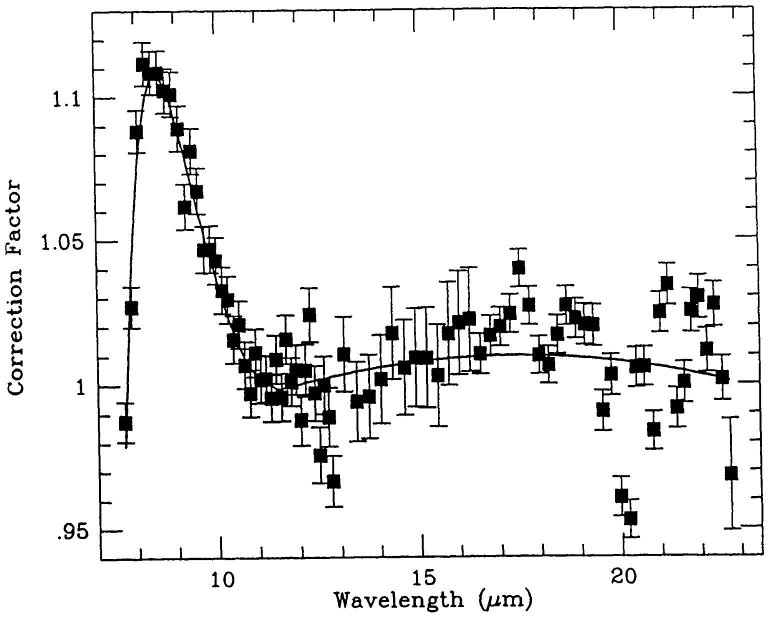

Fig. 6. Function required to recalibrate shape of LRS spectra. Solid interpolating lines represent best-fit polynomials to overlapping blue and red portions. To correct an LRS spectrum, divide it by this function.

## THE STELLAR ATLAS

The present efforts anticipate the development of an eventual grid of "real" calibrated stellar spectra intended to supplant "calibration" based on Planck functions. This grid should be a resource for both observers and theoreticians. Our coverage will be continuous between at least 2 and 23 μm (the long wave limit of the IRAS LRS) so the grid will be valuable to all modes of infrared observation (from ground, air, and space). Although initially at low spectral resolution, future long term efforts will be directed toward replacing these initial spectra by ones at higher spectral resolution. The foundation of this stellar grid is a relatively small group of normal stars, typically K0-M0III, well-observed in a variety of infrared regimes. Their individual spectral fragments in different wavelength regions will be assembled into a single 2 to ~30 μm spectrum for each star. All will be radiometrically calibrated on a common basis, with well-characterized sources of error.

## ACKNOWLEDGMENTS

It is a pleasure to thank Bob Kurucz for providing us with the new models for Vega and Sirius. We are grateful to Gene Milone, Alan Tokunaga, and Andy Young for critical input to these efforts.

## REFERENCES

Cohen, M., Walker, R. G., Barlow, M. J., & Deacon, J. R. 1992a, AJ, in press

Cohen, M., Walker, R. G., & Witteborn, F. C. 1992, AJ, in press

Cohen, M., Witteborn, F. C., Carbon, D., Augason, G., Wooden, D., Bregman, J., & Goorvitch, D. 1992b, submitted to AJ

Engelke, C. W. 1990, "Long Wavelength Infrared Calibration: Infrared Spectral Curves for 30 Standard Stars" (Report of Group 51, Lincoln Labs., MIT)

Hayes, D. S. 1985, in Proc. IAU Symposium 111, " Calibration of Fundamental Stellar Quantities", eds. D. S. Hayes, L. E. Pasinetti & A. G. Davis Philip (D. Reidel: Dordrecht, Holland), p.225

Rothman, L. S. et al. 1987, Appl. Optics, 26, 4058

Strecker, D. W., Erickson, E. F., & Witteborn, F. C. 1979, ApJS, 41, 501 [SEW]

Volk, K., & Cohen, M. 1989, AJ, 98, 1918