STELLAR CALIBRATION IN THE INFRARED: EXTENDING THE LEGACY OF THE KAO, ISO, AND MSX TO SIRTF AND BEYOND

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ABSTRACT

I describe the extension of a self-consistent framework for absolute infrared (IR) calibration, that currently embraces about 100 ground- and space-based filters and spectroscopy from several satellites, to SIRTF's instruments and beyond. Founded originally on empirical spectra derived from observations on NASA's Kuiper Airborne Observatory (KAO), the entire calibration context is traceable to emergent spectra from a pair of stellar atmospheric models for Vega and Sirius by Kurucz. The scheme unifies IR photometry and spectroscopy in the 1–35 μm range and has been extended to 300 μm in support of ISOPHOT. Recent analyses of calibration experiments from the Midcourse Space Experiment (MSX) have validated the basis for ISO and MSX calibrators, and demonstrated the absolute closure of the framework.

Building on new techniques originally proposed to support WIRE, this scheme is currently being extended to support cross-calibrators among all pairs of SIRTF instruments, and to the support of IRAC over a wide dynamic range. The hallmarks of the methodology remain its self-consistency with all our absolute stellar calibrators that underpin other satellites (COBE/DIRBE, Infrared Telescope in Space (IRTS), ISO, MSX), and the unification of photometry and spectroscopy. Calibrated products are complete, 0.1–35 μm, spectra of A0-5V and K0-M0IIIs, capable of furnishing optical/IR calibrators for arbitrary filters and spectrometers.

The intent is to expand the current all-sky network of absolute calibrators to a far fainter network suitable not only for SIRTF but also for ground-based 8–10m class telescopes, still self-consistently. Tests are also being performed to validate the extrapolations of these spectra to 300 μm by model atmospheres, through observations of the bright, secondary calibrators (K0-M0IIIs) in the millimetre regime to see whether FIR-emitting chromospheres are present that could compromise extrapolations based upon purely photospheric radiation.

Key words: instrumentation: photometers, spectrographs - infrared: general - flux calibration

1. INTRODUCTION

I will take the position that part of the reason that ISO, along with several other missions, was so well-calibrated is that all were underpinned by a common, self-consistent, calibration basis that was already in place at the time of each launch. The clear lesson learned from these successes is that one needs a self-consistent common basis as much to bind together the instruments on a given satellite, as to compare transparently with data from different spaceborne, ground-based and airborne facilities. Such a basis should unify photometry and spectroscopy as ours has done (Cohen et al. 1999): for the HIFOGS spectrometer on the KAO; the NIRS and MIRS on the IRTS; directly for three of ISO's instruments; and for the SPIRIT-III focal planes on MSX (Mill et al. 1994, Price et al. 1996). Although stars were too faint to calibrate LWS directly, its spectra of several K-giant calibration stars show flux levels and spectral energy distributions to be perfectly consistent (albeit with absolute uncertainties of order 15-20%) with LWS's formal calibration from planets, as Tanya Lim has stated at this meeting.

How was this achieved? Building on a solid foundation of work from the ground, airplanes, and satellites we have been able to establish a robust IR calibration framework which I will summarise. Then I will briefly document the all-sky network of absolute 1.2–35 μm K0-M0III calibration stars that supported these missions; cite the validations of these calibrators accomplished by MSX; describe how the network is being extended to embrace SIRTF and, in principle, how it could go beyond even this; talk about dynamic range, wavelength range, spectral resolution, and sky distribution of the net; and will close with current tests of the extrapolations of these empirical spectra as far as 300 μm that we provided for ISOPHOT, based on Duane Carbon's model atmosphere calculations.

2. ABSOLUTE IRRADIANCE CALIBRATION WORK

The work I discuss is founded on a decade of effort by my colleagues, most frequently and notably Duane Carbon, Mike Egan, David Goorvitch, Peter Hammersley, Tom Megeath, Stephan Price, Russ Walker, Fred Witteborn, and myself. In the course of this work we have been able to unify ground-based, airborne, and spaceborne photometry and spectroscopy. Everything is based on a pair of hot stellar atmosphere models and their emergent spectra created by R. L. Kurucz. By calibrating spectra of cool stars with respect to identically obtained spectra of Vega or Sirius we were able to delineate the photospheric absorptions that appear in cool giants, principally the CO 4.7 μm and SiO 8.0 μm fundamentals. In the early years of IR astronomy, the assumption that every potential calibrator radiated as a blackbody at its effective temperature led to the neglect of these absorptions, resulting in specious "bumps" and wrongly shaped continua for any objects "calibrated" using these cool stars.

3. A COMMON CALIBRATION CONTEXT

Throughout, we emphasise the self-consistency and traceability of our calibrated products, and the provision of meaningful quantitative errors. The peer-reviewed absolute spectra are published in The Astronomical Journal and can be obtained over the Web by following links in this ongoing series of papers (Cohen et al. 1999). We have supported the stellar calibrators for COBE/DIRBE, CLEMENTINE, MSTI, IRTS, MSX, ISO, and most recently SIRTF and 2MASS, and thereby offer a common calibration context for infrared astronomy.

4. THE CURRENT CALIBRATION NETWORK

We have so far established almost 450 stellar calibrators, each represented by absolute 1.2–35 μm spectra. At the base of our "inverted pyramid" lies the pair of Kurucz model spectra for Sirius and Vega (Cohen et al. 1992a). Above come the dozen "composites", so-called because their **empirical** spectra (**not models**) were assembled from overlapping spectra secured from a variety of platforms and ratioed to spectra of Sirius or Vega identically obtained (Cohen et al. 1992b). By correcting a composite for extinction and lightly smoothing in an information-preserving fashion, its shape is applied to other stars of the same spectral type, after applying their own reddening to the shapes or "templates". Templates are normalised by scaling their measured irradiances (assessed from independently determined but consistently calibrated photometry) to those derived by integrating the appropriate relative spectral response curves for the filters, detectors and, when relevant, mean site-specific atmospheric transmission curves. Each piece of photometry yields a scale factor and the inverse-variance weighted mean of all available scale factors sets the adopted overall scale for the reddened templates. Currently, there are 422 published fainter template stars.

5. VALIDATING ABSOLUTE 1.2–35 MICRON SPECTRA

Anyone who works in absolute IR calibration owes a great debt to MSX. A great deal of the time it devoted to astronomy during its cryo-mission was spent on calibration activities. In particular, the "CB-06" experiment (Cohen et al. 2001) was tasked with validating the relative and absolute calibration of a subset of the composites. By using two "triads" (single experiments in which 3 stars are measured in all 6 MSX bands sequentially within about a 30-min period), it was possible to intercompare directly 5 composites (α Boo was the star in common to one pair of triads). All five were validated **relatively** (i.e. in terms of the comparison of observed and predicted magnitude differences between α Boo and the other 4 stars).

Twenty four such triad experiments were carried out by MSX enabling the comparison of the measured and predicted **absolute** irradiances of these stars. A set of 9 fiduciary calibrators (γ Cru, α Boo, β Peg, γ Dra, α Lyr, β Gem, β And, α Tau, α CMa) was validated in this fashion, to within 1% at 8.3 and 12.1 μm, 3% in the two shortest bands near 4.3 μm, and within 7.5% in the least sensitive band at 21.3 μm. This analysis ties together the two stars represented by models, and several of the composites. A further extension of this work relates pairs of fainter calibrators (previously published templates) to a fiducial star in each triad experiment. This effort validated 28 of these templates, and generated new versions (with reduced overall uncertainties) by including these MSX data in the template normalisations. In this fashion we have been able to validate spectra in all three tiers of our network of calibrators.

6. EXTENDING TO FAINTER LEVELS

The mid-infrared dynamic range of the current network of K0-M0IIIs is $\sim$150: IRAS $S_\nu(12\mu\text{m})$ spans the range 800 to 5 Jy. How do we extend this to support future satellites? Templating a K0-M0III needs only a spectral type, A_V, and characterised IR photometry.

The MSX PSC1.2 offers $\sim 35\times$ better spatial resolution than IRAS with roughly 330,000 point sources to $S_\nu(12\mu\text{m})>$ $\sim$50 mJy. If MIR photometry were the only limitation then MSX data could help to create standards $> 100\times$ fainter than current tertiaries.

Similarly, using the IRTS/NIRS PSCs one could identify multiply-observed, stable, faint K0-M0IIIs with co-added, absolutely calibrated, 1.4-4.0 μm spectra of good S/N. Because NIRS is calibrated in our common context (Freund et al. 1997), these spectra would certainly suffice to normalise templates to a level $S_\nu(12\mu\text{m})\sim$5 mJy (100-1000 times below current brightnesses).

For SIRTF we are now utilising Landolt Standards, exquisitely measured in $UBVRI$, distributed around the celestial equator and, in place of templates, have developed "super-templates" (0.11-35 μm) spectral shapes that are to be applied to potential calibrators at flux density levels 250$\times$ below current templates, or $S_\nu(12\mu\text{m})\sim$20 mJy.

The approach is first to test how well one can predict the observed NIR magnitudes solely from those at optical wavelengths using the super-templates. Two test sets under study are: a subset of the Landolt $UBVRI$ stars that have Tenerife JHK measurements by P. L. Hammersley; and an A-dwarf subset of the Carter-Meadows "faint standards" with $UBVRI$ and JHK measured at the South African Astronomical Observatory. Note that Tenerife and SAAO NIR photometry are the anchor points in our set of well-characterised, calibrated relative spectral response curves (RSRs)(Cohen et al. 1999). In general it is our goal to secure our own optical spectra in support of this program, and we have been successful to flux density levels $\sim 1000\times$ below the current tertiaries.

Incidentally, using the same subsets of stars we intend to derive the "zero point offsets" (see Cohen et al. 1999 for their definition) for 2MASS to complete the extension of our context to 2MASS, so that we can use 2MASS JHK to support further SIRTF/IRAC and cross-calibrators by normalising super-templates.

Note that, for this extension to SIRTF, a set of model atmospheric spectra of A-dwarfs was commissioned from, and kindly provided to us by, Dr. R. L. Kurucz. These are used exactly like empirical, cool, stellar template spectra but enable the generation of fainter IR calibrators than K0-M0IIIs because of the essentially zero colour indices of A-dwarfs (except in the presence of significant reddening).

In principle, one could continue indefinitely using faint stars with 2D MK spectral types and accredited photometry (also calibrated independently in our scheme) and quantitative uncertainties. In reality, however, one soon exhausts standard spectral catalogues once V$> 8 - 10$, hence the need to mount new ground-based classification spectroscopy programs (Megeath's talk, this meeting). Colour based searches for candidate K0-M0III stars based solely on (B-V) are plagued by severe contamination by foreground cool dwarfs. For example, at the NEP, one expects only 27% of the total number of stars in the K- and M-type range to be giants. But, by using the Lick Northern Proper Motion Survey (Klemola et al. 1987) to select stars of the right colour, and applying the "reduced proper motion method" (Chiu 1980) to eliminate dwarfs by their detectable motions (giants are more distant and show no motions), we have succeeded in selecting 90% of a sample of potential SIRTF calibrators to be K-MIIIs (see also Megeath's paper).

The method does need well-characterised optical photometry and, for the test phase, relies heavily on (Landolt) $(U)BVRI$, but we have also calibrated the Hipparcos and Tycho (H$_p$, B$_T$, V$_T$) bands in our context. To go fainter, one must mount one's own optical CCD campaigns on the ground.

7. THE TEST RESULTS

To illustrate the details of the technique we offer the example of the Landolt K3III, SA105-205, with an A$_V$ of 0.35. Table 1 shows the scale factors derived from normalising the irradiances that result from integrating Landolt's CTIO $UBVRI$ bands (after combining filter, detector and atmosphere) over the correctly reddened K3-giant super-template to those independently implied by the $UBVRI$ magnitudes and our definition of zero magnitude in these bands. The resulting factors are combined using inverse-variance weighting to give an overall scale factor of 2.098e-3, with a fractional uncertainty of 0.2%. Note that this is only one component of several that contribute to the total absolute uncertainties associated with a super-template. Using the same reddened 0.11-35 μm super-template, scaled by this factor, enables the prediction of the Tenerife JHK magnitudes by integration of their RSRs over the spectrum. Ideally we want the spectrum to pass through all the NIR points, rather than systematically above, or below, all three. Therefore, the appropriate criterion for an acceptable prediction is that the "mean algebraic deviation" (MAD) of the signed differences at J, H, K be close to zero (Table 2). For this star the MAD is -.006m, highly satisfactory. Consequently, having quantitatively demonstrated that optical and NIR irradiances are consistent for the combination of type and extinction, we can legitimately merge all such points, and include Tycho, better to constrain the scale factor (2.137e-3$\pm$0.2%: see Table 3), which results in the spectrum plotted in Fig. 1 where one sees the panoply of ground-based and Tycho optical points and the Tenerife JHK points superposed correctly (at their isophotal wavelengths) on the scaled, reddened, K3III super-template spectrum. As a concrete example of what a faint calibrator made this way would look like, I offer Figure 1 which shows, in $(\lambda, \lambda^4 F_\lambda)$ space, the mean spectrum of SA105-205 (solid curve), with its $\pm 1\sigma$ bounds (dashed), and the optical/NIR pho-

Table 1. The new technique of optical normalisation of the super-template for a Landolt K-giant, SA 105-205, K3III, A$_V$=0.35, using Landolt's $UBVRI$ filters.

Filter	Scale	Frac.Unc.	$\lambda_{iso}(\mu$m)
LU	1.492e-03	6.243e-03	0.3618
LB	2.220e-03	4.382e-03	0.4442
LV	2.112e-03	3.584e-03	0.5454
LR	2.213e-03	3.094e-03	0.6436
LI	2.063e-03	3.068e-03	0.8049

Table 2. Predicting Tenerife JHK from the optically normalised spectrum.

Filter	Pred. mag.	Unc.	Obs. mag.	Diff.
TCSJ	6.298	0.009	6.320	0.022
TCSH	5.675	0.006	5.628	-0.047
TCSK	5.483	0.005	5.491	0.008

Table 3. Now normalise with ALL photometry.

Filter	Scale	Frac.Unc.	$\lambda_{iso}(\mu$m)
LB	2.220e-03	4.382e-03	0.4442
LV	2.112e-03	3.584e-03	0.5454
LR	2.213e-03	3.094e-03	0.6436
LI	2.063e-03	3.068e-03	0.8049
B$_T$	1.768e-03	5.116e-02	0.4340
V$_T$	1.952e-03	2.246e-02	0.5372
TCSJ	2.057e-03	1.211e-02	1.2584
TCSH	2.192e-03	7.465e-03	1.6433
TCSK	2.082e-03	5.607e-03	2.1583

tometry (filled circles) used to normalise it (all points are plotted at their isophotal wavelengths).

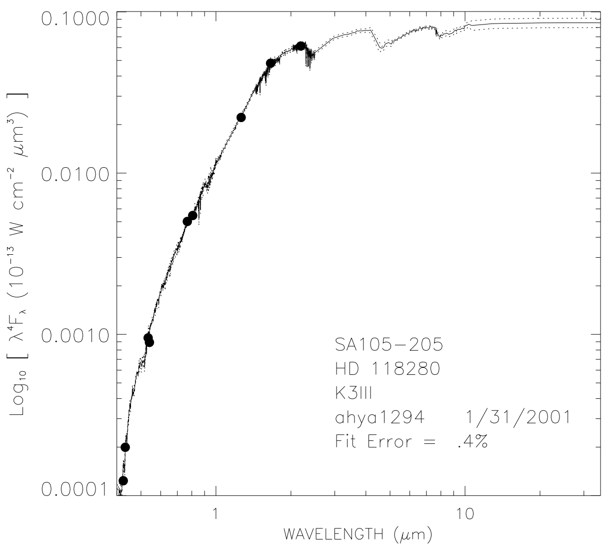

Figure 1. Super-template spectrum of SA105-205=HD118280 and its supporting photometry.

If one further integrates the 2MASS RSRs over this spectrum one can compare the observed and predicted 2MASS JHK (Table 4). The algebraic differences between these provide the first set of zero point offset values (specifically, for this star, -.008±.029, +.067±.041, -.018±.042 at JHK respectively) of what we hope will be a set of at least 20 such faint calibration stars, which should yield not only a good estimate of these offsets but also of their uncertainties, all of which are folded into the error budget on the calibrated spectrum. The objective of this approach is not merely to generate these faint calibrators, but to maintain a rigorous and self-consistent framework, so that the new faint calibrators can be used as readily as their published bright counterparts, and to insure the capability to merge SIRTF, ISO, MSX, DIRBE, etc. data transparently, without arcane adjustments or magnitude transformations.

This approach naturally links optical and IR calibrators, and will be applied to IRAC's calibrators and to a set of selected SIRTF cross-calibrators for all pairs of instruments. Of course, this technique can be only as good as the laboratory characterisation of the instruments' RSRs (e.g., see Hora's talk for IRAC). Further details of IRAC's equivalent of ISO's "GBPP" are given by Megeath and Shupe at this meeting. Note that the resulting complete spectra will also be available to support IRS, and the MIPS 24 μm band.

Table 4. Comparison of predicted and observed 2MASS JHK: defining a set of "zero point offsets" for 2MASS.

Filter	Pred. mag.	Unc.	Obs. mag.	Unc.
2MJ	6.330	0.017	6.322	0.024
2MH	5.646	0.019	5.713	0.036
2MK	5.443	0.018	5.425	0.038

8. DYNAMIC RANGE, λ, $\lambda/\Delta\lambda$, SKY DISTRIBUTION

We have already discussed enlarging the dynamic range of calibrators by following the methods outlined above for Landolt K0-M0IIIs and other carefully chosen A0-5Vs. By this approach the wavelength range has already been extended in going from the standard IR templates (1.2–35 μm) to the new super-templates (0.11-35 μm). Extrapolation of K/M-giants beyond 35 μm is possible using model emergent spectra. No wavelength limitations attend the use of the Kurucz A0-5V model spectra.

The K0-M0III super-templates and templates are low-resolution products in the IR (R=$\lambda/\Delta\lambda$ ~50-300 as a function of λ). These are adequate to support SIRTF's IRS low-resolution (R=60-120) mode, from 5.3–40 μm. The A-dwarf spectra are, of course, equally useful. For IRS in high-resolution (R=600) mode, from 10–37 μm, we advocate the use of A0-5Vs. The Kurucz model spectra exist in a wide variety of resolutions, essentially unlimited. In principle one could also use higher-resolution observed spectra from ISOSWS (e.g., AOT6) because these, too, are traceable to our reference spectra (see Decin's talk, this meeting).

The current network is all-sky while the Landolt extensions will follow the celestial equator. Because of its orbit, SIRTF needs the "Constant Viewing Zone", at the Ecliptic Poles, so these require emphasis. However, there will also be an Ecliptic Plane subnet for IRAC (every 30° in ELON, within 10° of the EP) for pre-/post-downlink times which occur close to the ecliptic.

9. TESTING EXTRAPOLATIONS FOR K-/M-GIANTS

To support ISOPHOT, NASA-Ames model emergent spectra (by D. F. Carbon) were used to extend the observed 1.2–35 μm spectra as far as 300 μm. These extrapolations were validated by ISOPHOT by comparing the overlap of their calibrators between planets, asteroids, and stars (see Mueller's talk, this meeting). However, to create these spectra it was necessary to assume that all these stars have single-component atmospheres; i.e. pure photospheres. The work of Wiedemann et al. (1994) work has shown that cool giants have temperature bifurcations so that material at common altitudes exists in two distinct temperature regimes: the chromosphere, and the radiative equilibrium region where the temperature is mediated by molecules. The balance between the contributions of these two regions to the overall spectrum of stellar radiation varies substantially between stars.

The bright secondary reference stars used as IR calibrators are precisely the "quiet" giants in which radiatively-cooled regions very largely dominate the stellar surfaces. Hence, in these stars, single-component models are most likely to be valid; e.g. α Boo, α Hya, α Tau, γ Dra.

In order to probe the outer atmospheric structure of the composites, to establish whether these radiate as expected, thereby showing the correctness of the stellar FIR calibration spectra) or possess long-wavelength chromospheres, as well as to connect mm-wave and FIR absolute flux calibrations, Jack Welch and I have begun to observe the K-/M-giants by aperture synthesis using BIMA at 1 and 3 mm in the continuum. So far we have imaged α Tau and α Boo. Mm-wavelengths sample the temperature minimum in these stars. Results suggest that both stars are well-behaved at 100 μm (IRAS) but there could be excess 3-mm flux in α Boo, on the basis of new CRAY models by Duane Carbon.

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