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IRRADIANCE CALIBRATION OF SPACE-BASED INFRARED SENSORS

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this work is to develop a basis for irradiance calibration of space-based infrared sensors. It is an extension of previous work that fully defines the context of the calibration, and the concepts of spectral composites and templates. We discuss four areas of work carried out during the past year; our accomplishments and failures; and our plans for the future. The four areas are:

1) Production and release of Version 3.0 of the Walker-Cohen Atlas of Calibrated Spectra,
2) Production and release of Version 1.1 of the Air Force Bright Spectral Atlas,
3) Extraction of zodiacal radiance data from the MSX Lunar OAR experiment DC32, and
4) Work on removing the non-rejected Earth radiance from MSX CB01 scans of the zodiacal dust near the Sun.

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1. INTRODUCTION

Satellites employing infrared sensors are continually being launched by space agencies, such as NASA and ESA and by the US DOD community. The successes of IRAS, ISO, IRTS, and MSX have already produced enormous infrared databases. Consequently, there must now be greater emphasis on data verification, validation, and calibration issues to assure that these data sets are of sufficient reliability for application to the quantitative design of advanced spaceborne sensors and systems. There is an urgent need not only to rationalize infrared calibration and place it in a common and well-defined context, but also to provide a network of calibrators well distributed across the sky, with a common traceable pedigree. This network should be sufficiently populated to have a member relatively close to any arbitrary direction because satellites and aircraft cannot afford major excursions in pointing to secure measurements of the few traditional calibration objects. Dynamic range, too, is an issue and such a network must include stars both fainter and brighter than today's popular "standards".

The purpose of this work is to develop a basis for irradiance calibration of space-based infrared sensors. It is an extension of previous work (Cohen, et al Papers 1-9, 1992-1998) that fully defines the context of the calibration, and the concepts of spectral composites and templates. This previous work culminated in the publication of *An All Sky Network of 422 Infrared Calibration Stars* (Cohen, et al 1999). Our approach is based on a self-consistent absolute framework within which radiometry and spectroscopy are unified, with wavelength coverage ideal for calibrating many satellite, airborne, and ground-based sensors.

Our work during the past year has been directed toward the following:
a) Production and release of Version 3.0 of the Walker-Cohen Atlas of Calibrated Spectra. This is an expansion of the original *All Sky Network of 422 Infrared Calibration Stars* to include results of the MSX observations and templates for additional spectral types,
b) Production and release of Version 1.1 of the Air Force Bright Spectral Atlas which includes all of the stars from Version 1.0 augmented by 320 new stars from the MSX Point Source Catalog (MSX PSC) (Egan, et al. 1999),
c) Extraction of zodiacal radiance data from the MSX Lunar OAR experiment DC32, and
d) Work on removing the non-rejected Earth radiance from MSX CB01 scans of the zodiacal dust near the Sun.

2. RELEASE 3.0 OF THE WALKER-COHEN ATLAS OF CALIBRATED SPECTRA

The 570 templates issued under Release 3.0 were formulated following essentially the same principles as in previous releases (Cohen et al. 1999, AJ, 117, 1864). However, several issues had arisen since Release 2.0 that necessitated some changes in the code, in the catchment area for stars to be templated, in the spectral types themselves, and in the range of templatable spectral types. The Explanatory Supplement to Release 3 reproduced in Appendix A fully describes these changes and their implementation. We will only summarize them here.

We built new spectral templates to fill previous gaps in our spectral coverage. This required construction of a K4 III template from interpolation between our K3 III (α Hya) and K5 III (α Tau) smoothed composites. To satisfy the need to handle any M-giant from M0-M4, we produced an α Cet (M1.5III) composite to create another smoothed template, filling in from M1-M1.5III. β Peg (M2.5II-III) serves to template M2-M3 III stars, and γ Cru (M3.4 III) was applied to M3.5-4III types.

We included many new stars and much new well-characterized photometry from the recent archives of the ISO "Ground-Based Preparatory Programme", the Mid-Infrared Spectrometer on the joint NASA-ISAS Infrared Telescope in Space mission (MIRS), the Midcourse Space Experiment (MSX) PSC-1.2 and CB06, and the DIRBE "BCC".

The release of the Fifth Volume of Michigan Spectral Types has had a major impact on our templates. Michigan Spectral Types, previously confined to the southern hemisphere, have become available for northern hemisphere stars. This required us to reevaluate all of the spectral types on which we base our choice of template.

3. RELEASE OF VERSION 1.1 OF THE AIR FORCE BRIGHT SPECTRAL ATLAS

The AFBSA is an independent set of calibrators selected to be among the IR-brightest sources in the sky. Our ultimate goal is to create complete (2-35 μm) spectra for all stars brighter than zero magnitude in the infrared. To do this we will eventually utilize IRAS Low Resolution Spectra (LRS), ISO SWS spectra, other groundbased and airborne spectral observations from the past and recent literature, as well as spectra generated by theoretical and/or empirical models. These will be normalized by means of well-characterized photometry to bring them into the photometric system described above.

Candidate stars for the AFBSC are selected from the IRAS all-sky survey, the Cal. Tech. Two Micron Sky Survey, and the MSX point source catalog. For inclusion in the catalog, a star must be brighter than zero magnitude in the respective survey bands.

An updated issue of The Explanatory Supplement to the AFBSC, Version 1.1 is reproduced in Appendix B and fully describes the contents of the catalog and the methods used in its preparation. AFBSA Version 1.1 includes all of the stars from Version 1.0 augmented by 320 new stars from the MSX Point Source Catalog (MSX PSC) (Egan, et al. 1999).

The AFBSA Version 1.1 consists of 1397 ASCII files, one for each cataloged star, plus this Explanatory Supplement. The files are divided into three sub-directories; \Documentation, \Spectra, and \Standards. The catalog is made up of the following types of stars:

a) 122 non-variable stars of which 35 are previously published "standards"
b) 79 are K stars
c) 1275 variable stars
d) 1058 AGB stars - 778 are oxygen-rich stars and 280 are carbon stars
e) 472 stars classified variable due to their listing in the GCVS
f) 622 stars classified variable by IRAS
g) 1012 stars classified variable because they exceeded the 15% median absolute deviation threshold.

Thirty-five stars from our previously published models, composites and templates are zero magnitude or brighter at 12 μm. These have been included in the AFBSC Version 1.1, \Standards in their original published forms.

The Version 1.1 spectrum files consist of an extensive header identifying the star and the spectrum chosen to represent it, information relating to the production of the spectrum, and the basis for its variability status. Next is a list of all the photometry found for that star in the IRAS, MSX, and CIO catalogs with our spectral irradiance conversions at the tabulated wavelengths. Following the header, the spectrum is tabulated in columns of wavelength, spectral irradiance, irradiance uncertainty, and an estimate of the variability of the irradiance.

4. EXTRACTION OF ZODIACAL RADIANCE DATA FROM THE MSX LUNAR OAR EXPERIMENT DC32.

The DC32 experiments were designed to characterize the MSX SPIRIT III Out-of-Field-of-View-Rejection (OFVR) at off-axis angles within the SPIRIT III baffle cut-off by exploiting spatial coadding and the multiband nature of the radiometer for measurements near the Moon.

The Moon was used as the bright source of off-axis irradiance incident on the SPIRIT III telescope aperture. The SPIRIT III sensor scanned the sky in a narrow 30°-long field with the long axis of the detector array normal to the ecliptic plane and centered on or near a solar elongation of 180°. Full moon occurs at the time the Moon is at 180° solar elongation. Due to the motion of the Moon about the Earth, 18 MSX orbits prior to the orbit that scanned the full moon, the Moon was approximately 15° to the east of the field being scanned. On each subsequent MSX orbit the Moon approached the scanned field by an additional 0.84° to 1.1°. On the 19th orbit the scan passes over the Moon.. After another 18 orbits the Moon was 15° west of the scanned field. Scans that were made at the extremes of the field (± 15° from the Moon) were used to determine the sky background in spatial regions that were near the SPIRIT III baffle cut-off and thus expected to be essentially free of stray Lunar radiance. This natural sky background radiance was to be subtracted from all of the OFVR/BRDF scans in order to delineate that component of the total observed radiance due to mirror BRDF, baffles, etc. This same measurement scheme was applied to a number of lunar phases, not just full Moon.

We have reduced and processed the DC32 scans made at large angles to the Moon to extract the radiance of the zodiacal background at large (90° – 180°) solar elongations. The data were processed as follows:

a. **CONVERT 6.2.5:** This program accepted all the Level 1A data as an input and used radiometer extended source processing to convert to Level 2 data. DC32_02, 03, 04, 05, 06, 12, and 18 were processed using a Dark Offset Matrix file generated by Sean Carey (AFRL) while DC32_22, 24, 25, and 31 used the original version provided as part of the Level 1A data set.

b. **POINTING CONVERT 6.0.2:** The output from CONVERT is then processed by Pointing Convert and output as separate Extended Source Map files for each of the two scans in each DCE. The Definitive Attitude File was used to determine the start and stop UT for each scan.

c. **DC Offset determination:** The data has a number DC offsets which had to be removed prior to binning the data. The early DCEs, before DC32_18, have up to two offset measurements in each scan but increased to as many as 10 in each scan for DCEs above 18.

d. **Creating a Scan:** In order to process the map file and create a final scan, an IDL code was developed that included the following steps.

- **Dark Offset Effects:** It is not possible to make a reliable estimate of the dark offset correction until after the first dark offset measurement (shutter closed). Therefore the data from the beginning of the first scan to the end of the first offset was eliminated. In addition, data taken during a dark offset measurement had to be excluded from the radiance data set. Nine seconds of data were removed starting 2.5 seconds before the dark shutter was closed as determined from the housekeeping data file. The minimum and maximum ecliptic latitude in each offset measurement was also tracked and data were eliminated in this interval ± 0.5° due to the 1° width of the array.

- **Point Source Removal:** Point sources were removed using a median filter with a width of 45 pixels.

- **NRER Avoidance Zone**: To avoid contamination of the background radiance due to the Non-Rejected Earth Radiance, a threshold of 700 km was set for the tangent height. Data above this height were assumed to be free of NRER and the observed radiance primarily due to zodiacal dust emission. Data taken at lower tangent heights were not used in the image construction.

- **Image Construction:** The inverse variance weighted radiance samples were then binned into a one dimensional (ecliptic latitude) image. Each scan was treated independently. All scans lie between –20° and +20° of the ecliptic. The radiance data were binned into ecliptic latitude arrays of 12023 pixels spaced every

9.2819165 arcseconds. The mean and variance of radiance samples were calculated for each pixel. The effective longitudes of the pixel samples were calculated from the mean of the longitudes of the samples binned in that particular pixel. This process was repeated for each band.

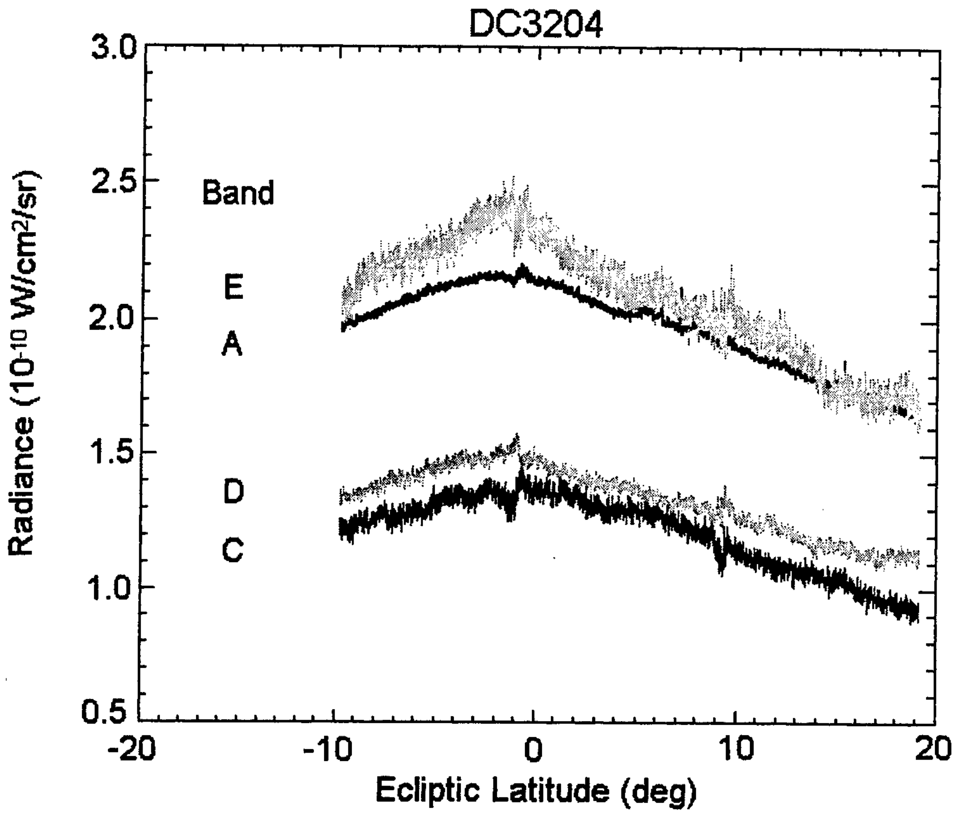

Figure 1. DC3204 scans across the ecliptic at a solar elongation of approximately 93 degrees. The general envelope and structure are due to zodiacal dust bands. The sharp discontinuities at about -1° and $+9^{\circ}$ are due to the dark offset corrections and/or removals.

e. Results: Figures 1 and 2 show two typical scans constructed by the above process. We believe dust bands dominate the shape and structure in both figures. It is difficult to separate the cloud profile from the bands with only a short range of latitude in the scans. This is particularly the case in Figure 2 where the proximity of the bands is expected to increase their width and spacing.

We have averaged the radiance in a 0.1degree latitude bin centered on the ecliptic for each scan of each DCE. These results are plotted in Figure 3 to examine the dependence of the zodiacal radiance on solar elongation. It is clear that the decrease from 90° to about 165° is followed by a rise at 177°. It is unclear whether we are seeing dust emission from the gegenschein or the effects of the asteroidal dust bands. Combining these data with those from the long scans in CB04 should resolve this question.

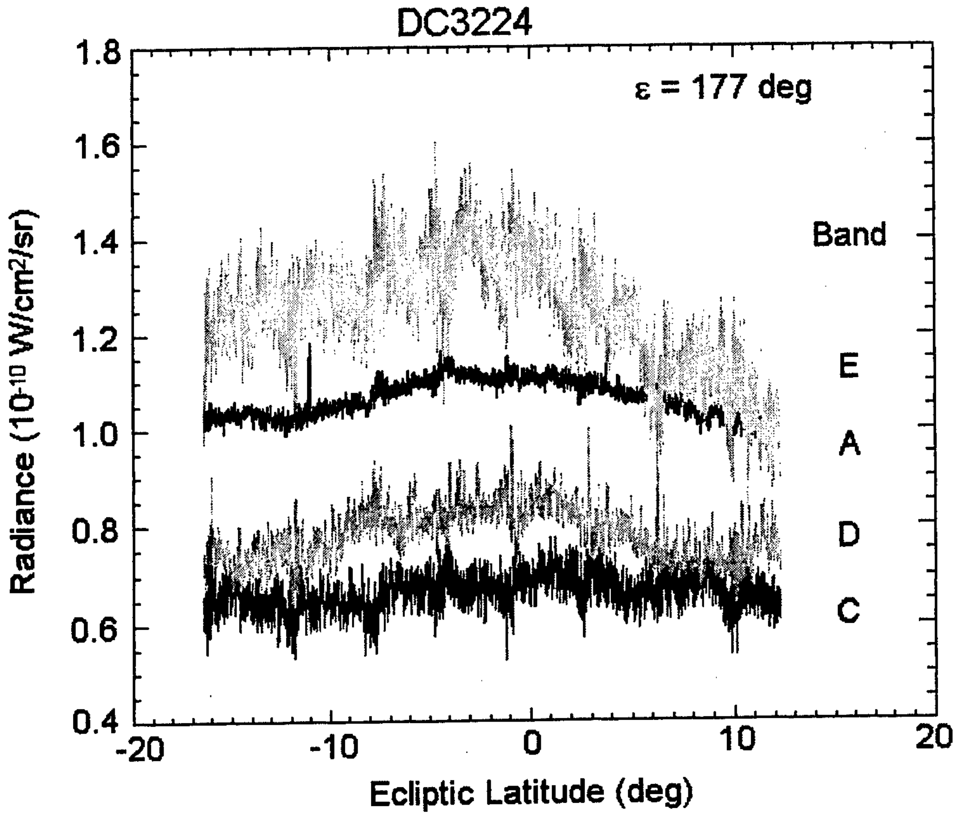

Figure 2. DC3224 scans made at a solar elongation of approximately 177 degrees. There were many dark offsets during this scan. The dark levels are well corrected here. The presence of dark offsets is revealed by the increased noise in the region of an offset due to the poor statistics.

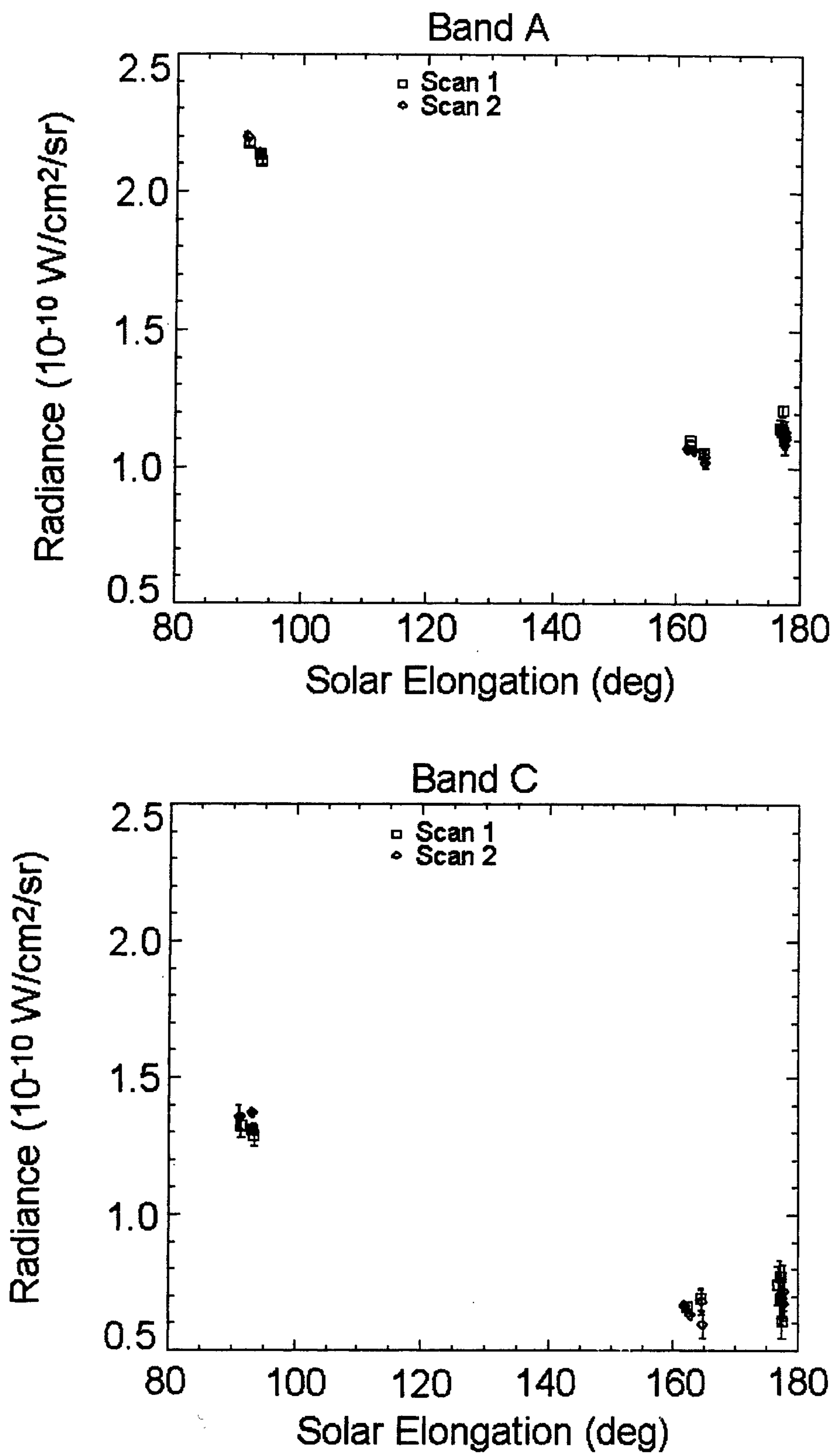

Figure 3. The radiance measured in SPIRIT III bands A and C at zero degrees ecliptic latitude vs solar elongation.

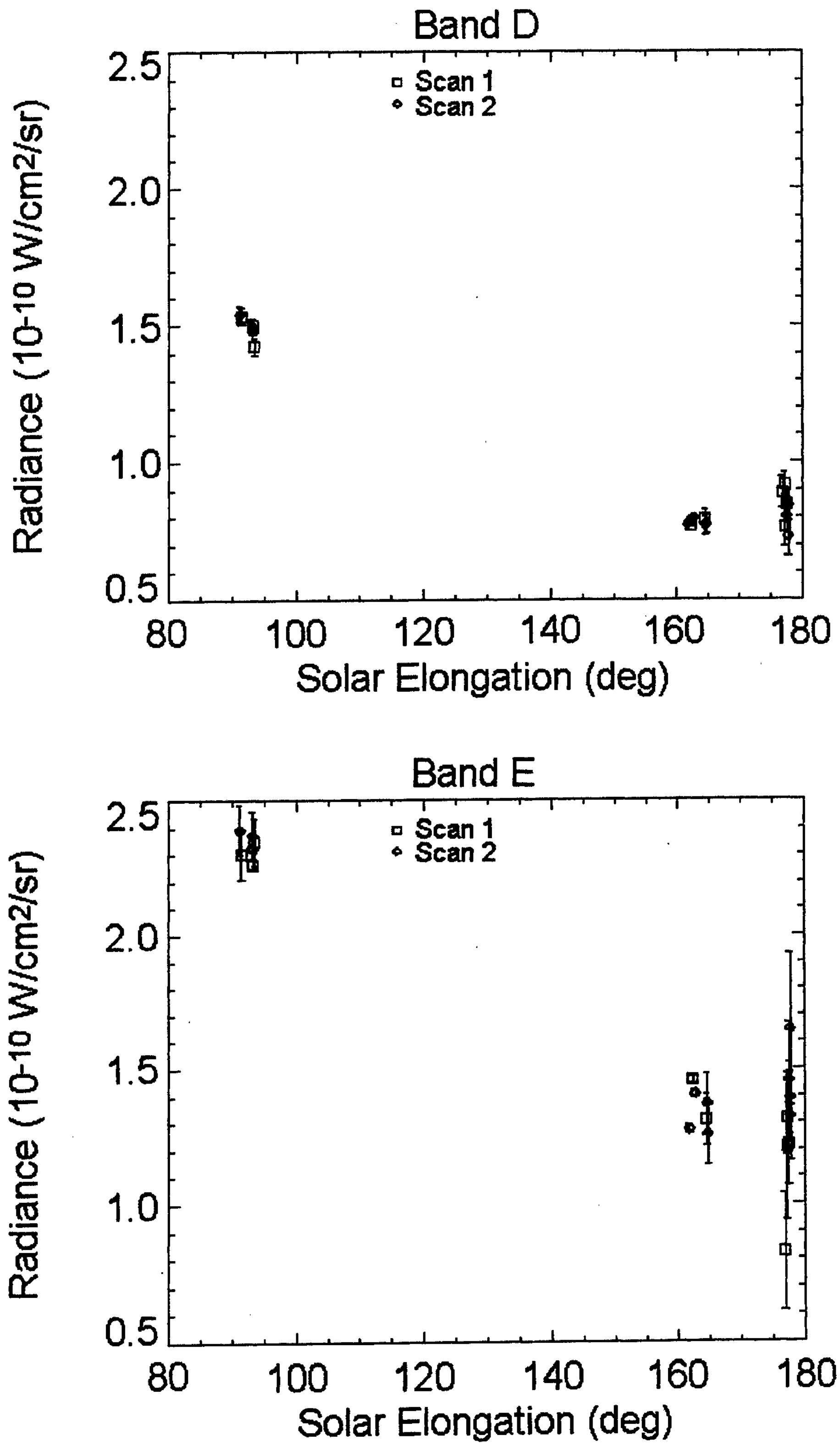

Figure 3. (continued) The radiance measured in SPIRIT III bands D and E at zero degrees ecliptic latitude vs solar elongation.

5. WORK ON REMOVING THE NON-REJECTED EARTH RADIANCE FROM MSX CB01 SCANS OF THE ZODIACAL DUST NEAR THE SUN.

The purpose of this analysis was to extract the zodiacal background signal from CB01 data contaminated by Non-Rejected Earth Radiance (NRER). These data were obtained in a celestial background experiment that was designed to measure the zodiacal flux close to the sun.

An empirical model for the NRER has been developed at Vanguard Research. This model is based upon the data obtained by MSX satellite as part of the DCATT data calibration experiment DC08. Our primary goal was to use the NRER model to correct for the contamination and thereby extract the zodiacal signal at small solar angles. Details of the process are given in Appendix C, Reduction And Analysis Of Celestial Background Experiment CB01 - Characterization Of The Zodiacal Background At Small Solar Angles, as well as an enumeration of the data sets delivered to AFRL.

Subsequent analysis of these data reveal several deficiencies which we have traced to the model NRER. The empirical model assumed that the source of the off-axis radiation, the Earth, was essentially constant during the scans of DC08 even though they were made over different topographies and on different days. It appears now that that was a poor assumption, and a working model should account for changes in the source. We believe that we have a workable approach to resolving this problem, and will pursue it during the next year.

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Cohen, M., Walker, R.G., Carter, B., Hammersley, P.L., Kidger, K.R., and Noguchi, K. 1999, "X. A Self-Consistent Radiometric All-Sky Network of Absolutely Calibrated Stellar Spectra", *Astron. J.*, **117**, 1864

Egan, M.P., Price, S.D., Murdock, T.L., Zweil, A., Burdick, S., Moshir, M.M., Tedesco, E., Bonito, N., Gugliotti, G.U., and Duszlak, J., 1999, *The Midcourse Space Experiment Point Source Catalog Version 1.2 Explanatory Guide*, Air Force Research Laboratory Technical Report, AFRL-VS-TR 1999-1522, ADA 381 933

APPENDIX A.

WALKER-COHEN ATLAS OF CALIBRATED SPECTRA EXPLANATORY SUPPLEMENT TO RELEASE 3.0

A1. Introduction

The 570 templates issued under Release 3.0 were formulated following essentially the same principles as in previous releases (Cohen et al. 1999, AJ, 117, 1864). However, several issues had arisen since Release 2.0 that necessitated some changes in the code, in the catchment area for stars to be templated, in the spectral types themselves, and in the range of templatable spectral types. This document describes these changes and their implementation in Release 3.0.

A2. New Composites And Stars To Template

A2.1. Walker-Cohen Atlas K4IIIs

Of the 573 WCA stars, we templated 422 in 1998-99, and the largest gap in our list of "template types" was represented by K4III. This was due to our inability to couple KAO 5-8 μm spectra of β UMi with any ground-based 1-5 μm spectral data (the star is simply too far north to be observed by the relevant telescopes that had good IR spectrometers available). This omission cost a total of 56 stars of type K4III (we handled K3.5IIIs using our K3III, and K4.5IIIs using our K5III template).

Therefore, we deemed it prudent to create a K4III "template" by interpolation between the smoothed K3 and K5 templates. To achieve this, we first separated the global and local biases from the purely uncorrelated uncertainties in the two flanking template spectra, and linearly interpolated between the random variances associated with the K3 and K5 spectra. Interpolation was linear, but in the quantity "s", described by de Jager & Nieuwenhuijzen (1987, *A&A*, **177**, 217), and demonstrated to be a far more linear mapping of spectral type than any quantity such as (B-V) or effective temperature. Local and global biases were interpolated by the identical method, then the three components of total error were reassembled for the final K4III template. Note also that this approach gave us the opportunity to regrid the K3III template (from α Hya in whose composite spectrum there still lingers a gap from 2.4 to 2.9 μm, never covered adequately with the existing KAO data) onto the continuous α Tau K5III spectrum. This eliminated this gap from the newly-built K4III spectrum.

However, as an end-to-end check of the reasonableness of the derived spectrum, we compared the K4 template with the shape of the β UMi KAO 5-8 μm spectrum, spliced to the 7.7-22.7 μm LRS spectrum. The agreement was satisfactory (i.e. within the observational uncertainties in the airborne and IRAS data), and we deemed it appropriate to proceed with this K4 "composite".

All that was then required, to apply the K4III template exactly as its forerunners, was an angular diameter calibrator. For this we used two stars for robustness: β UMi and β Cnc. The former is the brighter of the two yet its angular diameter is the more poorly measured: Dyck et al. 1998 (AJ,116,981) give 9.7+/-0.8 milliarcsec, compared with β Cnc measured by Nordgren et al. 1999 (AJ,118, 3032) who give 5.03+/-0.04 milliarcsec. Both were used, with β UMi, templated with the K4III construct, used to fix the correct fractional uncertainty and β Cnc to determine the correct angular diameter scale.

A2.2. ISO Calibrators

Following the demonstrated success of ISO's calibration, and our paper showing that MSX and ISO are equivalent radiometrically in terms of the observed MSX irradiances of over 100 stars that were originally selected to support ISO's potential need for a network of absolute calibrators, we tackled 46 stars of the ISO "Ground-Based Preparatory Programme". These were templatable cool giant stars that had been erroneously represented for ISO purposes by Kurucz models. All these "calibration spectra", of course, lacked the SiO fundamental and were based on outdated CO line strengths. Consequently, our goal was to reissue their spectra as CWW templates, appropriate for their types. These stars are, therefore, included in Release 3.0 and often are significantly fainter than the IRAS 12 μm flux density limit of 5 Jy that characterized our earlier release.

A2.3. MIRS Calibrators

In the intervening 2.5 years since Release 2.1 templates were first created, we have received requests from the Japanese for help in calibrating their Mid-Infrared Spectrometer on the joint NASA-ISAS Infrared Telescope in Space mission. This mission covered 7% of the sky and the need was to provide as many absolute calibrators as possible in that fraction of the sky. The brightest stars well-detected by MIRS (a 32-element array of detectors covering 4.6-11.6 μm continuously) were extracted and their names provided to us. We selected a number of stars for which it seemed we might be able to offer templates if we could significantly extend our range to M4III.

Consequently, founded upon our γ Crucis composite (M3.4III), we extended as far as M4III templates. Some of the stars selected for MIRS were wildly variable, or have spectra that in no way resemble γ Cru's energy distribution. These objects were never made into MIRS calibrators and have not been issued in Release 3.0. However, 19 stars became valuable MIRS calibrators and, therefore, appear among the new templates.

To satisfy the need to handle any M-giant from M0-M4, we also used the α Cet (M1.5III) composite to create another smoothed template, filling in from M1-M1.5III. β Peg (M2.5II-III) serves to template M2-M3 stars, and γ Cru is applied solely to M3.5-4III types.

A2.4. DIRBE "BCC" Calibrators

We have further exercised DIRBE's own calibration network, whenever those stars have templatable types (we abandoned all stars later than M4III), drawing from the 92 objects in the "BCC" archive discussed by Mitchell et al. 1996 (AIP Conf.Proc., 348, 301). This is permitted because we have already demonstrated (Paper IX: Cohen, 1998, AJ 115, 2092) that DIRBE faithfully replicates our calibration context.

A3. New Photometry Resources

A3.1. Literature & ISO GBPP

To provide normalizations for all these additional templates we found a handful of additional photometry archives in the published literature that were traceable as to passband, uncertainties, and zero points (e.g. Kerschbaum et al. 1996, A&A, 118, 397). A major new resource came about because of the public release of even more ISO GBPP supporting photometry, primarily from Hammersley, both broadband (JHK) and narrowband Selby-type (Jn,Kn,Ln). These sufficed to normalize the many ISO Hipparcos-selected cool giants.

A3.2. MSX

Following our paper based on the CB06 DCEs, we have now incorporated the ability to use either PSC1.2 or CB06 data in template normalization.

A3.3. DIRBE "BCC" Data

We are content to utilize DIRBE photometry for BCC stars, but only after proper allowance for the uncertainties that arise in each band. These are a consequence of the uncertainties in solid angle for each of bands D1-D4, and the Poisson fluctuations in the background around each star to be templated, in addition to the regular statistical errors derived from the very large number of measurements per band per star.

A3.4. The Role Of IRAS

In previous releases of templates, we could count on the existence of 4 meaningful PSC/FSC flux densities at 12/25 μm for each star. However, with the increased diversity of stars now, and the associated faintness of some objects, this is no longer the case. We have modified the template code to be capable of addressing a wide variety of less than ideal but real-life situations, such as no PSC data yet FSC are present; no 25 μm flux densities, only those at 12 μm, be they PSC or FSC; etc.

A4. New Spectral Types

The release of the Fifth Volume of Michigan Spectral Types has had a major impact on our templates. Finally, this single-person, consistent effort at spectral classifications has crossed the celestial equator, necessitating a reevaluation of all the types on which we base our choice of template. Our choice is, as in 1998-99, 1. Michigan; 2. Perkins Revised; 3., and a poor choice even for third place, the BSC version 5 (whose rich detail of declared types obscures the fundamental heterogeneity and incorrectness of most). Consequently, we aligned the choices for all 662 stars available for the new release to follow this rigid prioritization. Thus, even if some stars have only the same photometry as was available to us for Release 2.1, they could still be represented in Release 3.0 by a different template because their spectral types may have been reclassified by the Michigan project in the intervening years.

A5. Templates

Templates are fashioned virtually exactly as before in terms of their header information. After their final creation, all 570 spectra were inspected to determine how well they fit their photometry, to check for erroneous photometry and/or uncertainties, and for correct transfer of names, etc. We visually examined our associated plots of these products to cull inappropriate data. All 570 passed inspection.

A6. An Overview

A6.1. Template Types

The breakdown by template types is as follows:
81 β Gem (K0); 106 α Boo (K1.5); 93 α Hya (K3); 76 β UMi (K4); 120 α Tau (K5); 67 β And (M0); 8 α Cet (M1.5); 10 β Peg (M2.5); 9 γ Cru (M3.4).

A6.2. Template Extinctions

468 of the 570 stars suffer zero extinction; the remaining 102 stars have extinctions between 0.03 and 1.70 magnitudes, with only 25 values exceeding 0.50 magniude.

A6.3. Normalization Biases

Template normalization biases vary from 0.44% to 5.37%. Of these, 220 have bias $\leq$1%, 402 $\leq$ 2%, 490 $\leq$ 3%, and 512 $\leq$ 4.0%. Above 4%, biases usually correspond to normalizations based on IRAS data only.

A6.4. Angular Diameters

Radiometric angular diameters range from 0.33 to 14.73 milliarcsec.

A6.5. Amount Of Photometry Per Template

The minimum number of pieces of normalizing photometry was 4; the maximum, 25. With 4 pieces there are 58 templates; with 5, 97; 6, 40; 7, 74; 8, 74; 9, 37; 10, 42; 11, 32; 12, 23; 13, 13; 14, 19; 15, 11; 16, 10; 17, 7; 18, 8; 19, 8; 20, 4; 21, 3; 22, 3; 23, 6; and with 25 pieces 1.

APPENDIX B

AN EXPLANATORY SUPPLEMENT TO THE AIR FORCE BRIGHT SPECTRAL CATALOG, Version 1.1

B1. Introduction

Satellites employing infrared sensors are continually being launched by space agencies, such as NASA and ESA and by the US DOD community. The successes of IRAS, ISO, IRTS, and MSX have already produced enormous infrared databases. Consequently, there must now be greater emphasis on data verification, validation, and calibration issues to assure that these data sets are of sufficient reliability for application to the quantitative design of advanced spaceborne sensors and systems. There is an urgent need not only to rationalize infrared calibration and place it in a common and well-defined context, but also to provide a network of calibrators well distributed across the sky, with a common traceable pedigree. This network should be sufficiently populated to have a member relatively close to any arbitrary direction because satellites and aircraft cannot afford major excursions in pointing to secure measurements of the few traditional calibration objects. Dynamic range, too, is an issue and such a network must include stars both fainter and brighter than today's popular "standards".

In previous work (Cohen et al. 1992-1998, Papers I-IX) we have developed a basis for irradiance calibration of space-based infrared sensors, and have fully defined the context of the calibration, and the concepts of spectral composites and templates. This work culminated in the recent publication of *An All Sky Network of 422 Infrared Calibration Stars* (Cohen et al. 1999). In the above series of papers we have described a consistent effort to provide absolutely calibrated broad and narrowband IR photometry based upon a carefully selected, IR-customized pair of absolutely calibrated stellar models for Vega and Sirius. These hot stellar models have been employed as reference spectra to calibrate the spectra of cool giants. This approach has yielded a valuable set of secondary stellar standards with calibration pedigrees directly traceable to the two primary standards. These cool giant spectra are totally unlike any blackbody, and are dominated by the fundamental absorption and overtones of CO, SiO, and water vapor. Thus the ideal (IR-bright) calibrators have significant spectral structure that is not yet adequately modeled by stellar atmospheric codes but that can be approached in a rigorous observational manner. These (almost) entirely observed 1.2-35 μm absolute spectra of all reference stars are designated "composite spectra" (because of the method of their assembly).

Each composite spectrum has been used to create many calibrated stellar spectra, all with a traceable common calibration heritage, given a single prerequisite, namely photometry in a "well-characterized" system of filters. To achieve this goal, one must make the fundamental "template assumption", that the dereddened (for interstellar extinction) infrared spectral shape of any observed K0-M0 giant accurately represents the intrinsic spectrum of any other giant with the same two-dimensional spectral type as the composite from which the "template" is created. The adopted template (spectral shape) is reddened appropriately for the star that was spectroscopically unobserved in the IR, then normalized by matching the template's in-band radiometry to the measured in-band irradiances in a set of filters. The *All Sky Network of 422 Infrared Calibration Stars* referenced above was produced using this technique.

It has become clear that current demand for on-orbit calibration of space-based programs, such as SBIRS, requires brighter calibration sources than are available within the present network of 422 stars.

B2. The Air Force Bright Spectral Catalog (AFBSC)

The AFBSC is an independent set of calibrators selected to be among the IR-brightest sources in the sky. Our ultimate goal is to create complete (2-35 μm) spectra for all stars brighter than zero magnitude in the infrared. To do this we will eventually utilize IRAS Low Resolution Spectra (LRS), ISO SWS spectra, other groundbased and airborne spectral observations from the past and recent literature, as well as spectra generated by theoretical and/or empirical models. These will be normalized by means of well-characterized photometry to bring them into the photometric system described above.

Candidate stars for the AFBSC are selected from the IRAS all-sky survey, the Cal. Tech. Two Micron Sky Survey, and the MSX point source catalog. For inclusion in the catalog, a star must be brighter than zero magnitude in the respective survey bands.

The brighter in the mid-infrared the required calibrators are, the greater the likelihood of encountering abnormal stars such as heavily dust-shrouded, long-period, cool variables. At the present time we lack detailed information on the spectral variations of these stars with the phase of their light curves, even for those objects whose variations are supposedly periodic. Thus, we anticipate the need to revisit this catalog in subsequent versions, once we have learned more about the characteristics of variability among these IR-bright evolved stars. Variability of the majority of the IR-bright stars is the foremost problem to be addressed if these objects are to be accepted as reliable calibrators.

B2.1 AFBSC Version 1.1

AFBSC Version 1.1 is an extremely limited version that does not pretend to achieve the overall AFBSC goals either in quantity or quality of the sources. It is a result of an initial "testing of the waters" and serves a number of useful purposes. It alerts the systems designer to the potential bright calibrators that will be available to him for calibration of his spacebased, groundbased, and airborne IR systems. The irradiance levels and dynamic range possible are well-defined, even though many absolute irradiance levels have, at present, unacceptably large uncertainties for radiometric calibration. Many of these will still be useful astrometric calibrators and knowing the range of their irradiances will improve infrared acquisition by enabling discrimination among multiple objects in the field. Further, many stars are identified in this version that do have reliable and non-varying irradiances with acceptable errors, and are immediately applicable for radiometric calibration. Finally, production of this version of the catalog has identified to the authors those stars that can be readily elevated to precise calibration status, and those that will require gargantuan efforts.

AFBSC Version 1.1 includes all of the stars from Version 1.0 augmented by 320 new stars from the MSX Point Source Catalog (MSX PSC) (Egan, et al. 1999).

B2.1.1 The Stars

In Version 1.0 we have limited our choice of stars to those brighter than zero magnitude at 12μm in the IRAS PSC2. Our search returned 1638 point sources. Identification of these sources revealed that 198 were non-stellar objects (71 planetary nebulae, 126 HII regions, and 1 galaxy). In addition we removed 3 T Tauri stars and 2 young OB stars. These were deleted, reducing the input list to 1435 IR bright stars. We further required that additional infrared photometry beyond that of IRAS be found for each star in either the MSX PSC (Egan et al. 1999) or the Catalog of Infrared Observations (CIO), Edition 5.0 (Gezari et al. 1999). Thirty-two stars that had no CIO or MSX photometry were also deleted, resulting in a final input list of 1403 stars.

In Version 1.1 we have included stars from the MSX PSC that were not reported in the IRAS PSC2. These sources are primarily near the galactic plane. Many were seen as confused or blended with other sources by IRAS due its large fields of view. These have been resolved by MSX, and reliable photometry obtained.

From the large MSX database we selected 1701 sources seen by MSX in at least two of the six bands and were brighter than zero magnitude in, at least one of the bands. These were associated by position with the IRAS PSC2 and the IRAS Working Survey Database[1] and 1397 matches were found. The criterion for a match was that the position error ellipses should overlap at the 95% confidence level[2]. Multiple matches that could not be easily resolved were then dropped bringing the list to 1287. We next checked for stars that were already in Version 1.0, further reducing the list of new stars to 974.

B2.1.2 The Spectra

All of the stellar spectra presented in Version 1.1 are a combination of observed IRAS LRS spectra (Olnon & Raimond 1986) and SKY4 library spectra (Cohen 1993,1994). The LRS spectra meaningfully cover the spectral range from 7.67 μm to 22.74 μm and consist of two independent, overlapping segments. The spectral resolution, non-uniform sample interval, and photometric noise differ in the two segments. The absolute spectral irradiance of the LRS spectrum is set by normalization of the integral of the observed spectrum, weighted by the spectral response of the IRAS 12 μm detector, to the mean irradiance observed in the IRAS 12 μm band. Thus the LRS spectrum is

[1] The association is necessary to find IRAS photometry and LRS extractions.

[2] (The MSX error ellipse was assumed a circle of 1 sigma radius = 2 arcsec, the 95% confidence level was then 2.45*2 = 4.9 arcsec. The IRAS error ellipse was as given in the PSC2 and projected in the direction of the MSX detection).

brought into the stellar calibration context to within the uncertainties of the noise in the integration process and the error of the IRAS 12 μm in-band irradiance, the latter usually being dominant.

SKY4 is an analytical model describing the statistical distribution of point sources within our galaxy. Its purpose is to predict counts of point sources versus limiting irradiance observed at any specific wavelength (or band) along an arbitrary, but given, line-of-sight through the galaxy. SKY uses a library of spectra for 87 classes of objects to achieve its wavelength flexibility. These spectral shapes cover the range 2 μm to 35 μm, are tabulated at 0.1 μm intervals, and were constructed from observed spectral fragments and model stellar atmospheres. In the AFBSC Version 1.1 the SKY spectra are spliced to the calibrated LRS spectra to create hybrid spectra extending from 2 μm to 35 μm. This process makes maximum use of the observed LRS spectra for each star to allow for intrinsic variations of spectral shape that occur within a given spectral class.

Each star must be placed in one of the 87 SKY4 spectral classes to select the proper SKY spectrum to splice to the LRS. MK spectral types were used for those stars with measurements in the visible spectrum and previously classified. The remainder of stars were initially classified by their position in the [12]-[25], [25-60] color-color plane (Walker & Cohen 1988). A second classification was made by least-squares fitting the LRS data to all the 87 spectra of the SKY4 library. The SKY spectrum with minimum variance from the LRS was considered an alternate possibility. In those cases where the two classifications differed, resolution was sought by examining the trends of short and long wavelength photometry. This was an interactive procedure, wherein the SKY spectra and available photometry were displayed with the LRS spectrum (Figure 1). With the photometry as guidance the "most reasonable" of the two SKY spectra was selected along with the wavelengths for the long and short wavelength splices (Figure 2). At this point the candidate star was rejected from the catalog if the photometry did not offer a clear choice between spectra, or if neither of the SKY spectra provided a good fit to the observed LRS spectrum. An additional 235 stars were rejected by this procedure. The final choice of spectral class is given in the header of each spectrum file.

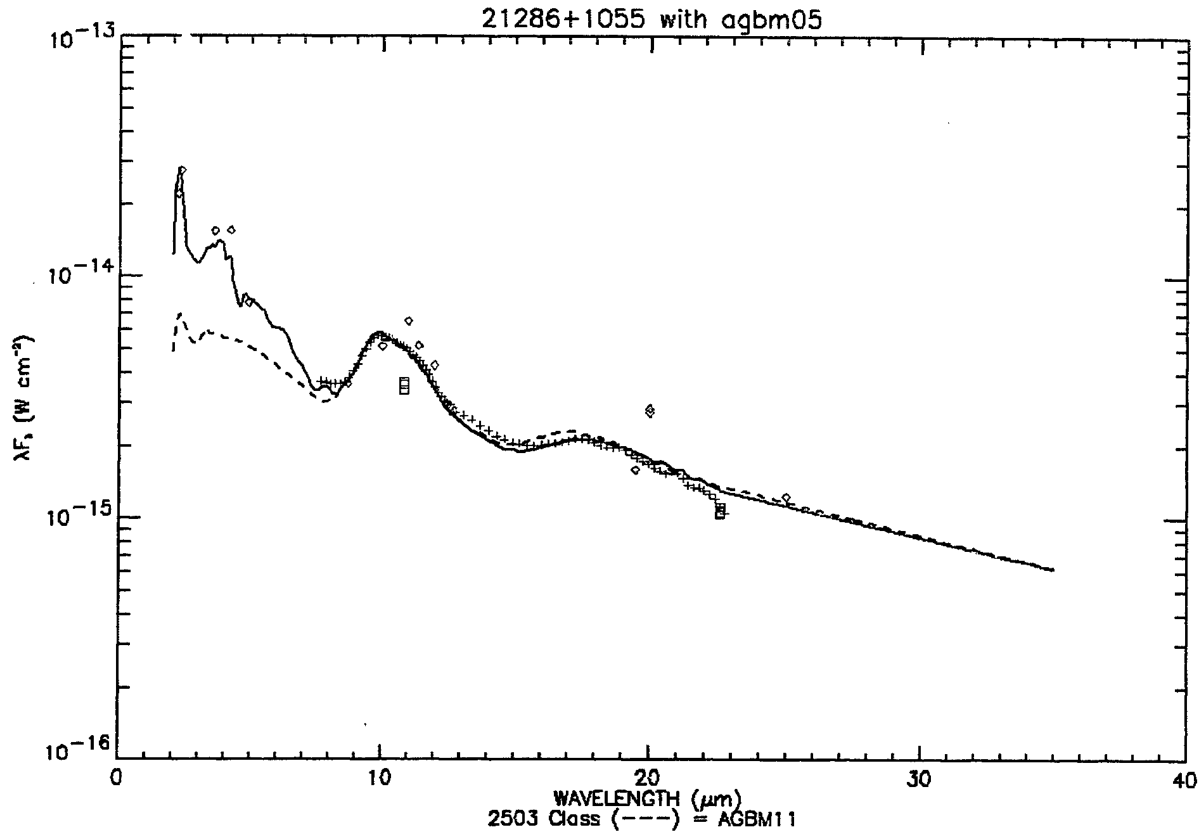

Figure B1. LRS and two candidate spectra over-plotted with the available photometry. The crosses are the LRS spectrum. The dashed curve is the SKY 4 spectrum defined by the location of the star in the [12- 25], [25-60] μm color plane. The solid curve is the SKY 4 spectrum selected by the "best-fit" criterion to the LRS. This is a good example in which short wavelength photometry resolves the ambiguity. Diamonds are points from CIO photometry, squares are from IRAS.

B2.1.3 The Photometry

IRAS, MSX, and CIO photometry were used in developing the AFBSC Version 1.1. As discussed in Section B2.1.1 above, the absolute spectral irradiance of the LRS spectrum was set by normalization to the mean irradiance observed in the IRAS 12 μm band. This normalization established the irradiance scale for the entire 2 to 35 μm spectrum through splicing of the long and short SKY spectrum segments to the LRS. The rest of the photometry was used as a guide to spectrum selection and to estimate the magnitude of the star's irradiance variability.

IRAS and MSX photometry are defined within the calibration context described in Section B1. However, the photometry given in the CIO is, at best, an inhomogeneous collection of measurements referenced to a variety of photometric "standards" whose absolute irradiance values have been revised repeatedly during the ensuing years. Furthermore, no measurement uncertainties are tabulated in the CIO.

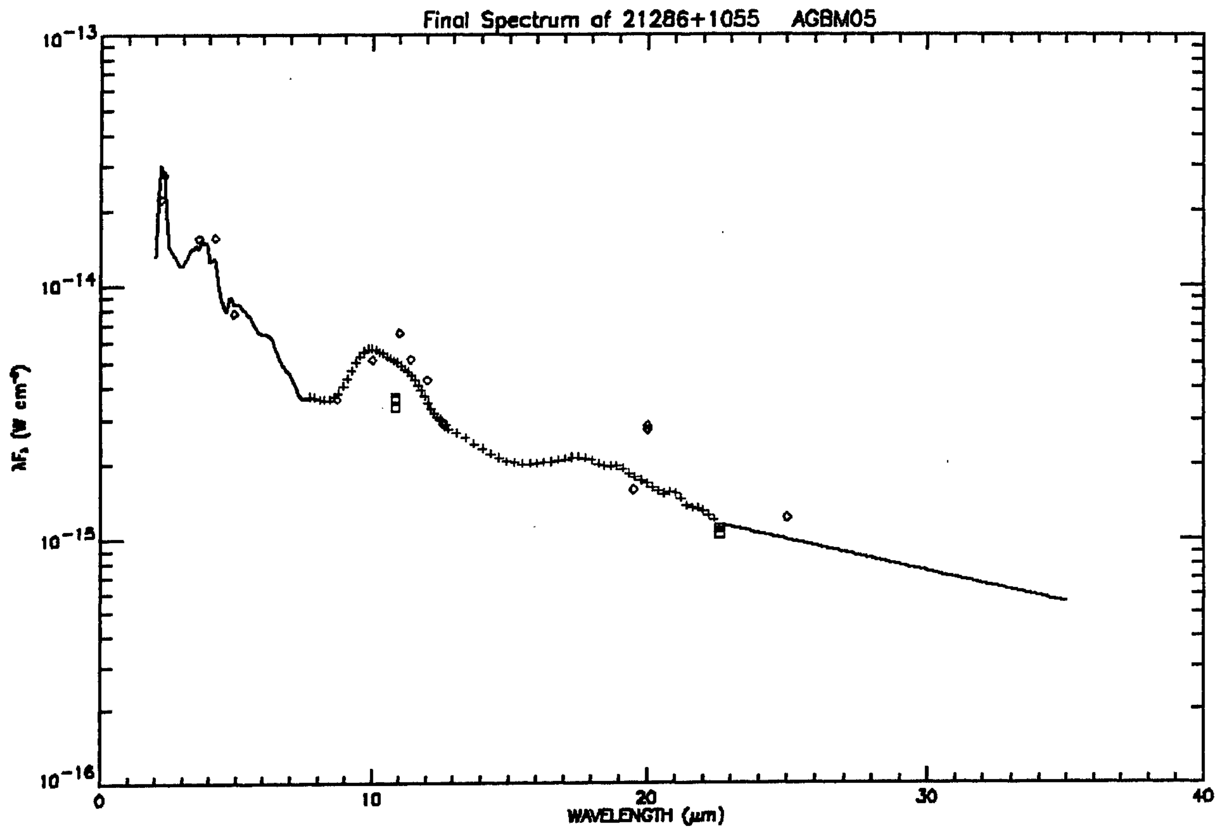

Figure B2. The final spectrum of the star after selection of the AGBM05 SKY 4 spectrum and splicing to the LRS. As before, the crosses are the LRS, and the solid line is the extrapolation using the SKY 4 spectrum.

The CIO photometry must be brought into the calibration context common to IRAS and MSX. A reliable re-calibration of this photometry requires knowledge of the complete instrumental spectral response, atmospheric extinction at the time and place of observation, the standards used, their assumed irradiances, and the photometric errors. We are searching the literature for this information; however, at present we do not have it. Faced with a choice of discarding the CIO data, using it as is, or using it after performing "zero-order" calibration, we opted for the latter. This would not have been a good choice if we had wished to use the photometry to establish the irradiance scale of the spectra. *AFBSC Version 1.1 uses IRAS to fix the irradiance scale. CIO and MSX photometry are used only to guide spectrum selection and estimate variability.*

We chose a monochromatic approach to the re-calibration in which we assumed that the wavelength tabulated in the CIO was the isophotal wavelength appropriate to the measurement passband when observing an A0V star. This assumption can lead to a significant source of error in the re-calibrated fluxes of different spectral types. Amplitude data in the CIO are given in a wide range of units (flux, flux density, magnitudes, etc.) corresponding to the units tabulated in the original reference. Codes are included in the CIO to specify the units of the amplitude. Amplitudes were converted to spectral irradiance at the isophotal wavelength using the code. If the amplitude was given in magnitudes it was converted assuming that zero magnitude had been adopted for Vega (A0V), and that the magnitudes had been derived from the ratios of the observed monochromatic flux of the star to that of Vega at the isophotal wavelength. This process was carried out for all 1403 stars in our list. It produced 22867 "zero-order" calibrated photometric measurements.

We next searched the CIO for measurements of our model (2: Cohen et al. 1992a), composite (12: Cohen et al. 1996), and template (422) calibration stars (Cohen et al. 1999) that were observed at the same time as the 1403. Correction factors were derived from comparison of the spectral irradiances predicted for these calibration stars by the above procedure with those measured. By this technique we were able to improve the values of 60% of the above 22867 measurements. For most reference sets multiple observations were available and mean factors and their standard deviations (σ) were derived. Typical values of σ were a few percent. Seventeen factors with $\sigma > 15\%$ were excluded.

All the photometry found for each star is included in the header of the spectrum file. Our conversion to spectral irradiance is also tabulated there.

B2.1.5 Spectral Irradiance and Spectral Irradiance Uncertainties

As described in Section B2.1.1, the absolute spectral irradiance of the LRS spectrum (~7.67 μm to 22.74 μm) is determined by normalization to the mean IRAS 12 μm in-band flux. This calibration is extrapolated to cover the range 2 to 35 μm by splicing segments of SKY4 spectra to both long and short LRS wavelengths. Splicing is done interactively. The spectra are displayed and the wavelengths for the splices selected. The SKY spectrum is sampled at three overlapping LRS wavelengths at each end, and the median scale factors and their variance determined for the splice. The spectra are then redisplayed and may be iterated to produce the smoothest fit. Selecting the wavelength of the splice to exclude a region of excess noise in the LRS spectrum is permitted.

Uncertainties in the spectral irradiance arise from: 1) the error in the mean IRAS in-band flux, 2) noise in the LRS spectrum, 3) errors in the splices, 4) errors in the shape of the SKY4 spectrum chosen, and 5) error in the absolute spectral irradiance of the standard star, Vega. All of these error sources, with the exception of the shape errors in the SKY4 spectra, are included in our estimates of the spectral irradiance uncertainties. We use the uncertainty IRAS provides with each of its measurements ("RELUNC"). We calculate the noise in the blue and red segments of the LRS spectra separately, since these usually differ. Splice errors were calculated along with the splicing scale factors. The absolute error in the Vega flux is 1.45% (Cohen et al. 1992a).

The spectra of stars are expected to vary continuously throughout a given spectral class, and thus will differ from any specific spectrum chosen to represent that class. Given enough samples of the spectra of the class the variance could be determined. This has not been done for the SKY4 spectra, and this source of error has not been included in our estimates of the spectral irradiance uncertainties.

B2.1.5 Variability

As previously noted, variability of the majority of the IR-bright stars is the foremost problem to be addressed if these objects are to be accepted as reliable calibrators. It is quite likely that both the shape of the spectrum and overall irradiance level vary with the phase of the star's light curve. The LRS spectrum representing the star is actually a mean spectrum composed of measurements taken at different times (different phases) during the 300 days that IRAS was active. It is thus a poorly determined mean spectrum of the star for the epoch 1983, and we would not expect it necessarily to be representative in detail of the spectrum taken at any other epoch.

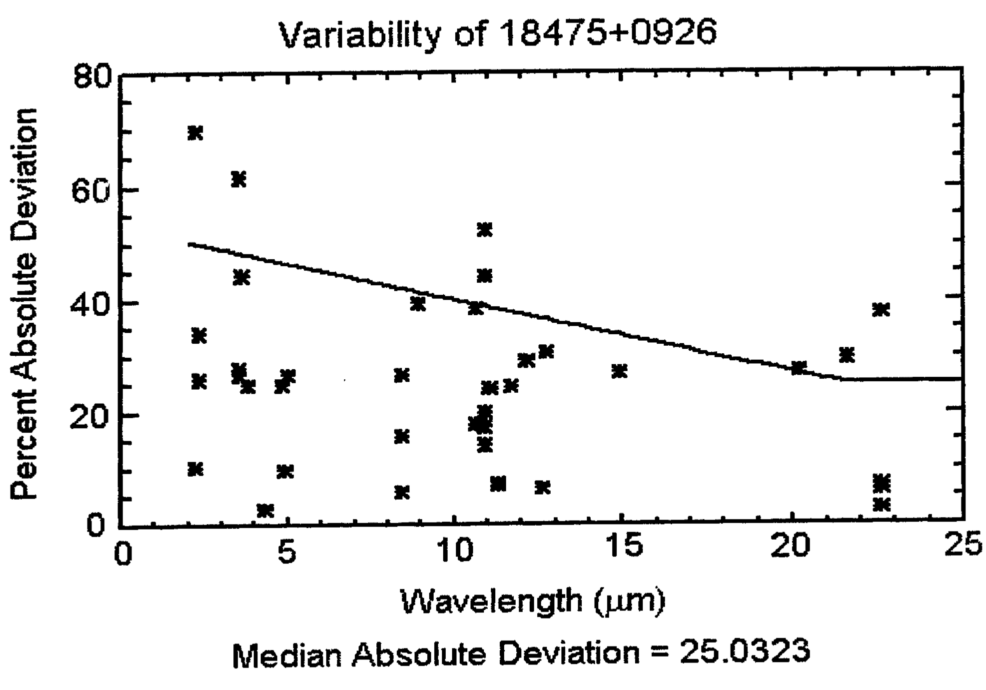

Figure B3. A typical variability curve. The solid line is a linear least squares fit weighted to approximate an upper envelope fit to the absolute deviations of the photometry from the adopted spectrum. A threshold is applied at the level of the median absolute deviation.

To date, only a few stars have adequate infrared photometry throughout a complete light cycle. Even fewer have spectral observations as a function of phase. It is not possible at this time for us to make a comprehensive assessment of the spectral variations of each star in the AFBSC Version 1.1. We have chosen instead to provide an estimate of the magnitude of the problem, star by star, based on the absolute deviation of the available photometry from the spectrum that we have selected to represent that star. This method's only virtue is that it uses the observations; however, it suffers from a number of deficiencies.

First, we have not been able to place all the photometry into a consistent calibration context. We have also not been able to evaluate the errors in the original photometry nor have we accounted for additional errors that we have introduced in our re-calibration process. For example, comparison of data at incorrect isophotal wavelengths can introduce significant errors, as can neglect of possible "beam-size" effects. The estimate of variability we provide will then be some sort of upper-limit to the expected deviations, since photometric uncertainties are included.

MSX photometry was taken during 1996/97, while the CIO photometry spans 1964-1997. Typical periods for IR-bright variables are hundreds of days. If a star has a large number of photometric observations, the chances are good that we have samples near both maximum and minimum phases, and our estimate of the range of variability is valid. A star with only a few photometric observations is likely to not be sampled over its entire amplitude, and we will have underestimated its variability.

We consider a star to be variable if: 1) it is listed in the General Catalog of Variable Stars (GCVS), 2) if the IRAS PSC2 VAR flag is greater than or equal to 50, 3) if the median absolute deviation of the photometry from the spectrum is greater than 15%[3] or 4) if the star was classified as an AGB star. The third criterion was added when it became obvious from the photometry that a number of variable stars were not being classified as variable by the first two criteria. Stars with no visual counterpart do not appear in the GCVS. Stars that were inadequately sampled by IRAS (ex: 2HCON vs 3HCON sky) fail the second criterion. Using the above rules, 91% of the stars in the AFBSC Version 1.1 were classified as variables.

The actual measure of spectral variability that we have adopted and tabulated in the spectrum files resulted from a linear fit to the upper envelope of the absolute deviations versus wavelength, the fit being constrained to not fall below a threshold at the median absolute deviation. Figure B3 is an example of a typical variability curve. We expect the real spectral variability to be much more complex than can be represented by a linear relationship. For example, one might expect to observe greater amplitude of variability within spectral emission and absorption features than in the stellar continuum. The measure we have given is at best crude, however, it serves as a warning to the user to be aware that the star is variable and that the irradiance observed at any future epoch may differ from that tabulated in the spectrum file. In many cases, the tabulated variability is a useful upper and lower bound (±) to the expected range of irradiance variations.

[3] The mean of the median absolute deviations of the photometry observed for 10 composites (standards) was 5.4 ± 1.9 %, yielding a conservative threshold at the mean + 5σ from the mean, that is, 14.9 ≈ 15 %.

B2.1.6 The Catalog

The AFBSC Version 1.1 consists of 1397 ASCII files, one for each cataloged star, plus this Explanatory Supplement. The files are divided into three sub-directories; \Documentation, \Spectra, and \Standards. The 1362 files in \Spectra are written in the format discussed in Section B2.1.7, while those in \Standards are in the formats in which they were originally published.

The catalog contains the following:

a) 122 non-variable stars of which 35 are previously published "standards"

b) 79 K stars

c) 1275 variable stars

d) 1058 AGB stars - 778 are oxygen-rich stars and 280 are carbon stars

e) 472 stars classified variable due to their listing in the GCVS

f) 622 stars classified variable by IRAS

g) 1012 stars classified variable because they exceeded the 15% median absolute deviation threshold.

Thirty-five stars from our previously published models, composites and templates are zero magnitude or brighter at 12 μm. These have been included in the AFBSC Version 1.1, \Standards in their original published forms. Table B1 lists these stars and relates the spectrum file name to the IRAS name.

B2.1.7 Format of the AFBSC Version 1.1 Spectrum Files

The names of the spectrum files in the \Spectra subdirectory were constructed from the star's IRAS name plus a letter designating the source of the name and an extension consisting of the AFBSC and its Version number. For example: 00254-1156_P.AFBSC11; 00254-1156 is the IRAS name, the P indicates that the name originated in the IRAS PSC2 catalog (a letter M indicates it originated in the MSX catalog), and the AFBSC11 labels this as a spectrum file of AFBSC Version 1.1.

The AFBSC Version 1.1 spectrum files consist of an extensive header identifying the star and the spectrum chosen to represent it, information relating to the production of the spectrum, and the basis for its variability status. Next is a list of all the photometry found for that star in the IRAS, MSX, and CIO catalogs with our spectral irradiance conversions at the tabulated wavelengths. The bulk of the information is self explanatory, however, The CIO photometry section also includes three additional columns headed Code, Reference, and Star Names. The Code defines the quantity tabulated in the Magnitude column (see CIO Addition 5 for a complete listing). The Reference column contains a number identifying the original source of the data. The CIO Addition 5 gives the

Table B1. Previously Released Calibrated Stellar Spectra of Stars Brighter than Zero Magnitude.

MODELS		COMPOSITES		TEMPLATES	
STAR (IRAS Name)	FILE	STAR (IRAS Name)	FILE	STAR (IRAS Name)	FILE
06429-1639	acma0791.cmp	04330+1624	atau0392.cmp	00238-4234	HD2261.tem
18352+3844	alyr0791.cmp	07422+2808	bgem0994.cmp	00376+5615	HD3712.tem
		08214-5920	ecar1295.cmp [3]	00410-1815	HD4128.tem
		09251-0826	ahya1294.cmp	02043+2313	HD12929.tem
		10193+4145	muuma0496.cmp	04537+3305	HD31398.tem
		12283-5650	gcru0396.cmp [4]	05033-2226	HD32887.tem
		14133+1925	aboo0997.cmp	07276-4311	HD59717.tem
		16433-6856	atra1295.cmp [5]	09180+3436	HD80493.tem
		17554+5129	gdra1295.cmp	09297-5648	HD82668.tem
		23013+2748	bpeg0392.cmp	10154-6104	HD89388.tem
				11284+6936	HD100029.tem
				13495+3441	HD120933.tem
				14037-3607	HD123139.tem
				15186-3604	HD136422.tem
				16117-0334	HD146051.tem
				16433-6856	HD150798.tem
				16469-3412	HD151680.tem
				17133+3651	HD156283.tem
				19438+1029	HD186791.tem
				19565+1921	HD189319.tem
				20442+3347	HD197989.tem
				22150-6030	HD211416.tem
				22274+4726	HD213310.tem

Notes:

1. All of the above spectra are part of Release 2.1 of the Air Force Calibration Atlas which can be obtained in its totality directly from Dr. Steve Price, Air Force Research Laboratory, L. G. Hanscom Air Force Base, MA. 01731, Email: Steve.Price@hanscom.af.mil.
2. These ASCII files are in different formats than the AFBSC Version 1 spectrum files. Information pertaining to the construction of the calibrated spectra is contained in the header as is explanatory data for the format and content of the tabulated quantities.
3. The spectrum (ecar1295.cmp) is incomplete, covers 2.9 μm to 35.0 μm.
4. The spectrum (gcru0396.cmp) is incomplete, covers 3.95 μm to 35.0 μm.
5. The spectrum (atra1295.cmp) is incomplete, covers 2.9 μm to 35.0 μm. For complete spectral coverage use the template spectrum HD150798.tem

complete list of reference papers. The final column lists some additional names for the star in question.

Following the header is the adopted spectrum tabulated in four columns. The first column is the wavelength (μm), the second is the spectral irradiance (W cm^{-2} μm^{-1}), the third is the uncertainty (1σ) in the spectral irradiance, expressed as a percentage of the irradiance, and the fourth column is the variability, also expressed as a percentage of the spectral irradiance.

The data span 2.0 to 35.0 μm. They are tabulated at 0.1μm intervals outside of the wavelength region occupied by the LRS. The limits of this region differ from one spectrum to another due to truncation of noisy or unusable portions of the LRS during the splicing process. Within the LRS region the wavelength intervals are those of the original, non-uniform, LRS samples.

Spectral irradiances and uncertainties are for the epoch (9 February - 22 November, 1983) of the IRAS LRS spectrum. The variability column is based on photometry that might have been observed at any time during 1964 to 1997. The data in the variability column are considered bounds, both upper and lower, on the expected range of the star's variability. These data are to be interpreted and applied as follows: if Δ_λ is the fractional variability[4], σ_λ is the fractional irradiance uncertainty[5], and $F_\lambda(t_o)$ is the spectral irradiance at the LRS epoch[6], then the spectral irradiance $F_\lambda(t)$ any other time can be expected to be

$$(1-\Delta_\lambda)\, F_\lambda(t_o) \le F_\lambda(t)\, (1\pm\sigma_\lambda) \le (1+\Delta_\lambda)\, F_\lambda(t_o).$$

A sample spectrum file follows.

```
IRAS PSC Name: 23587+6004
Common Star Name: WZ CAS
Spectral Class/Category: AGBC03

Air Force Bright Spectral Catalog (AFBSC) Version 1.0
Date and Time Spectrum Processed: May 29 14:43:55 2000
LRS Spectrum Used: 23587+6004.tst

=======================================================================
                            Variability Data

We consider a star to be variable if it satisfies any of the following
criteria: 1) it is listed in the General Catalog of Variable Stars (GCVS),
       or 2) if the IRAS PSC2 VAR flag is greater than or equal to 50,
       or 3) if the median absolute deviation of the photometry from the
             spectrum is greater than 15%,
       or 4) if the star is classified as an AGB star.

             Variable Star Listed in GCVS,    WZ CAS
             Variable AGB Star
             Variable, Median Absolute Deviation > 15 %
```

[4] The value in column 4 of the spectrum divided by 100.

[5] The value in column 3 of the spectrum divided by 100.

[6] The value in column 2 of the spectrum.

Mean Absolute Deviation =	81.1492 %
Median Absolute Deviation =	60.1009 %
Maximum Absolute Deviation =	330.112 %

===

Photometry Found

Infrared Astronomical Satellite (IRAS) Working Survey Database (WSDB)
Entries for each hours confirmed observation:

Wavelength (microns)	Irradiance (w/cm2/um)	Flux Density (Janskys)	Uncertainty (%)
10.84	8.776e-017	43.07	6.0
22.58	5.958e-018	13.26	7.0
10.84	9.055e-017	44.44	9.0
22.58	6.841e-018	15.23	10.0
10.84	9.128e-017	44.80	8.0
22.58	5.628e-018	12.53	10.0

Midcourse Space Experiment (MSX) Point Source Catalog, Version 1.2
See Egan. M.P. et al. 1999, The Midcourse Space Experiment Point Source Catalog Version 1.2 Explanatory Guide, Air Force Research Laboratory Technical Report, AFRL-VS-TR 1999-1522

Wavelength (microns)	Irradiance (w/cm2/um)
4.29	2.541e-015
4.35	2.677e-015
8.28	2.484e-016
12.13	5.876e-017
14.65	2.398e-017
21.41	7.847e-018

Catalog of Infrared Observations, Edition 5, Gezari D.Y., Pitts P.S., Schmitz M.,1999 available from NSSDC II/225:

Wavelength (microns)	Irradiance (w/cm2/um)	Magnitude (see code)	Code	Reference	Star Names
2.20	1.620e-014	1.040	M	850004	WZ CAS
2.20	2.240e-014	224.000	F	761005	WZ CAS
2.20	2.300e-014	0.600	C	650101	WZ CAS
2.20	2.640e-014	0.490	M	690001	IRC+60433
2.25	2.210e-014	0.570	M	810001	WZ CAS
2.25	2.520e-014	0.410	M	761005	WZ CAS
2.25	2.640e-014	0.430	M	800712	WZ CAS
2.28	2.230e-014	0.540	M	790401	AFGL 3196
3.12	4.870e-015	0.980	M	810001	WZ CAS
3.40	5.920e-015	59.200	F	761005	WZ CAS
3.50	4.440e-015	0.500	M	800213	AFGL 3196
3.50	4.750e-015	0.460	M	710203	WZ CAS
3.50	5.070e-015	0.340	C	650101	WZ CAS
3.50	5.510e-015	55.100	F	761005	WZ CAS
3.50	5.520e-015	0.230	M	790401	AFGL 3196
3.70	5.110e-015	0.240	M	810001	WZ CAS
4.20	3.390e-015	0.100	M	830610	RAFGL 3196
4.90	1.160e-015	0.540	C	710203	WZ CAS
4.90	1.200e-015	0.500	M	800213	AFGL 319[illegible]
4.90	1.360e-015	0.360	M	790401	AFGL 3196
4.90	1.440e-015	14.400	F	761005	WZ CAS
8.40	1.860e-016	0.230	C	710203	WZ CAS
8.40	1.910e-016	0.200	M	800213	AFGL 3196
8.40	2.300e-016	0.000	M	790401	AFGL 3196
8.40	2.350e-016	2.350	F	761005	WZ CAS
11.00	1.060e-016	1.060	F	761005	WZ CAS
11.00	9.340e-017	-0.040	C	710203	WZ CAS
11.20	7.360e-017	0.000	M	800213	AFGL 3196
11.20	8.570e-017	-0.160	M	790401	AFGL 3196
12.50	5.100e-017	-0.030	M	790401	AFGL 3196

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The Spectrum

Wavelength (microns)	Irradiance (w/cm2/um)	Irradiance Uncertainty (%)	Irradiance Variability (%)
2.00	8.589e-015	7.98	256.4
2.10	8.273e-015	7.98	253.2
2.20	7.798e-015	7.98	250.0
2.30	6.138e-015	7.98	246.8
2.40	5.008e-015	7.98	243.6
2.50	3.959e-015	7.98	240.4
2.60	4.019e-015	7.98	237.2
2.70	3.821e-015	7.98	234.0
2.80	3.950e-015	7.98	230.9
2.90	3.283e-015	7.98	227.7
3.00	2.076e-015	7.98	224.5
3.10	1.947e-015	7.98	221.3
3.20	2.365e-015	7.98	218.1
3.30	2.811e-015	7.98	214.9
3.40	3.010e-015	7.98	211.7
3.50	2.820e-015	7.98	208.5
3.60	2.619e-015	7.98	205.3
3.70	2.357e-015	7.98	202.1
3.80	2.019e-015	7.98	199.0
3.90	1.859e-015	7.98	195.8
4.00	1.772e-015	7.98	192.6
4.10	1.866e-015	7.98	189.4
4.20	1.850e-015	7.98	186.2
4.30	1.508e-015	7.98	183.0
4.40	1.283e-015	7.98	179.8
4.50	1.097e-015	7.98	176.6
4.60	9.837e-016	7.98	173.4
4.70	8.839e-016	7.98	170.3
4.80	7.805e-016	7.98	167.1
4.90	7.372e-016	7.98	163.9
5.00	6.746e-016	7.98	160.7
5.10	6.534e-016	7.98	157.5
5.20	6.015e-016	7.98	154.3
5.30	5.855e-016	7.98	151.1
5.40	5.874e-016	7.98	147.9
5.50	5.845e-016	7.98	144.7
5.60	6.421e-016	7.98	141.5
5.70	6.398e-016	7.98	138.4
5.80	6.509e-016	7.98	135.2
5.90	6.182e-016	7.98	132.0
6.00	6.048e-016	7.98	128.8
6.10	5.785e-016	7.98	125.6
6.20	5.510e-016	7.98	122.4
6.30	5.164e-016	7.98	119.2
6.40	4.818e-016	7.98	116.0
6.50	4.417e-016	7.98	112.8
6.60	4.237e-016	7.98	109.7
6.70	3.980e-016	7.98	106.5
6.80	3.601e-016	7.98	103.3
6.90	3.297e-016	7.98	100.1
7.00	3.132e-016	7.98	96.9
7.10	2.971e-016	7.98	93.7
7.20	2.778e-016	7.98	90.5
7.30	2.887e-016	7.98	87.3
7.40	2.713e-016	7.98	84.1
7.50	2.740e-016	7.98	80.9
7.60	2.681e-016	7.98	77.8
7.67	2.583e-016	9.41	75.4
7.86	2.489e-016	9.41	69.3
8.05	2.323e-016	9.41	63.5
8.23	2.207e-016	9.41	60.1
8.40	2.096e-016	9.41	60.1
8.58	2.025e-016	9.41	60.1
8.74	1.991e-016	9.41	60.1
8.91	1.933e-016	9.41	60.1
9.07	1.865e-016	9.41	60.1

Wavelength (microns)	Irradiance (w/cm2/um)	Irradiance Uncertainty (%)	Variability (%)
9.23	1.772e-016	9.41	60.1
9.38	1.658e-016	9.41	60.1
9.53	1.593e-016	9.41	60.1
9.68	1.526e-016	9.41	60.1
9.83	1.475e-016	9.41	60.1
9.97	1.412e-016	9.41	60.1
10.11	1.350e-016	9.41	60.1
10.25	1.330e-016	9.41	60.1
10.39	1.277e-016	9.41	60.1
10.53	1.226e-016	9.41	60.1
10.66	1.156e-016	9.41	60.1
10.79	1.102e-016	9.41	60.1
10.92	1.043e-016	9.41	60.1
11.05	9.944e-017	9.41	60.1
11.18	9.346e-017	9.41	60.1
11.30	8.689e-017	9.41	60.1
11.43	8.068e-017	9.41	60.1
11.55	7.757e-017	9.41	60.1
11.67	7.326e-017	9.41	60.1
11.79	6.820e-017	9.41	60.1
11.91	6.128e-017	9.41	60.1
12.03	5.777e-017	9.41	60.1
12.14	5.460e-017	9.41	60.1
12.26	5.288e-017	9.41	60.1
12.37	4.983e-017	9.41	60.1
12.48	4.689e-017	9.41	60.1
12.59	4.390e-017	9.41	60.1
12.70	4.308e-017	9.41	60.1
12.79	4.020e-017	14.11	60.1
13.09	3.635e-017	14.11	60.1
13.41	3.169e-017	14.11	60.1
13.72	2.919e-017	14.11	60.1
14.03	2.589e-017	14.11	60.1
14.33	2.500e-017	14.11	60.1
14.62	2.448e-017	14.11	60.1
14.90	2.445e-017	14.11	60.1
15.18	2.192e-017	14.11	60.1
15.46	1.946e-017	14.11	60.1
15.73	1.992e-017	14.11	60.1
15.99	1.837e-017	14.11	60.1
16.26	1.661e-017	14.11	60.1
16.51	1.631e-017	14.11	60.1
16.77	1.622e-017	14.11	60.1
17.02	1.451e-017	14.11	60.1
17.26	1.161e-017	14.11	60.1
17.50	1.141e-017	14.11	60.1
17.74	1.222e-017	14.11	60.1
17.98	1.179e-017	14.11	60.1
18.10	1.137e-017	10.99	60.1
18.20	1.115e-017	10.99	60.1
18.30	1.094e-017	10.99	60.1
18.40	1.074e-017	10.99	60.1
18.50	1.056e-017	10.99	60.1
18.60	1.040e-017	10.99	60.1
18.70	1.025e-017	10.99	60.1
18.80	1.010e-017	10.99	60.1
18.90	9.932e-018	10.99	60.1
19.00	9.761e-018	10.99	60.1
19.10	9.582e-018	10.99	60.1
19.20	9.398e-018	10.99	60.1
19.30	9.213e-018	10.99	60.1
19.40	9.030e-018	10.99	60.1
19.50	8.849e-018	10.99	60.1
19.60	8.673e-018	10.99	60.1
19.70	8.502e-018	10.99	60.1
19.80	8.336e-018	10.99	60.1
19.90	8.177e-018	10.99	60.1
20.00	8.026e-018	10.99	60.1

Wavelength (microns)	Irradiance (w/cm2/um)	Irradiance Uncertainty (%)	Variability (%)
20.10	7.884e-018	10.99	60.1
20.20	7.751e-018	10.99	60.1
20.30	7.627e-018	10.99	60.1
20.40	7.509e-018	10.99	60.1
20.50	7.396e-018	10.99	60.1
20.60	7.283e-018	10.99	60.1
20.70	7.168e-018	10.99	60.1
20.80	7.051e-018	10.99	60.1
20.90	6.930e-018	10.99	60.1
21.00	6.807e-018	10.99	60.1
21.10	6.680e-018	10.99	60.1
21.20	6.553e-018	10.99	60.1
21.30	6.426e-018	10.99	60.1
21.40	6.303e-018	10.99	60.1
21.50	6.187e-018	10.99	60.1
21.60	6.080e-018	10.99	60.1
21.70	5.981e-018	10.99	60.1
21.80	5.889e-018	10.99	60.1
21.90	5.801e-018	10.99	60.1
22.00	5.714e-018	10.99	60.1
22.10	5.627e-018	10.99	60.1
22.20	5.537e-018	10.99	60.1
22.30	5.448e-018	10.99	60.1
22.40	5.358e-018	10.99	60.1
22.50	5.270e-018	10.99	60.1
22.60	5.184e-018	10.99	60.1
22.70	5.095e-018	10.99	60.1
22.80	5.016e-018	10.99	60.1
22.90	4.938e-018	10.99	60.1
23.00	4.862e-018	10.99	60.1
23.10	4.787e-018	10.99	60.1
23.20	4.714e-018	10.99	60.1
23.30	4.642e-018	10.99	60.1
23.40	4.571e-018	10.99	60.1
23.50	4.502e-018	10.99	60.1
23.60	4.434e-018	10.99	60.1
23.70	4.367e-018	10.99	60.1
23.80	4.301e-018	10.99	60.1
23.90	4.237e-018	10.99	60.1
24.00	4.174e-018	10.99	60.1
24.10	4.112e-018	10.99	60.1
24.20	4.051e-018	10.99	60.1
24.30	3.992e-018	10.99	60.1
24.40	3.933e-018	10.99	60.1
24.50	3.876e-018	10.99	60.1
24.60	3.819e-018	10.99	60.1
24.70	3.764e-018	10.99	60.1
24.80	3.709e-018	10.99	60.1
24.90	3.656e-018	10.99	60.1
25.00	3.603e-018	10.99	60.1
25.10	3.552e-018	10.99	60.1
25.20	3.501e-018	10.99	60.1
25.30	3.451e-018	10.99	60.1
25.40	3.402e-018	10.99	60.1
25.50	3.354e-018	10.99	60.1
25.60	3.307e-018	10.99	60.1
25.70	3.261e-018	10.99	60.1
25.80	3.215e-018	10.99	60.1
25.90	3.171e-018	10.99	60.1
26.00	3.127e-018	10.99	60.1
26.10	3.083e-018	10.99	60.1
26.20	3.041e-018	10.99	60.1
26.30	2.999e-018	10.99	60.1
26.40	2.958e-018	10.99	60.1
26.50	2.918e-018	10.99	60.1
26.60	2.878e-018	10.99	60.1
26.70	2.839e-018	10.99	60.1
26.80	2.801e-018	10.99	60.1

Wavelength (microns)	Irradiance (w/cm2/um)	Irradiance Uncertainty (%)	Variability (%)
26.90	2.763e-018	10.99	60.1
27.00	2.726e-018	10.99	60.1
27.10	2.689e-018	10.99	60.1
27.20	2.653e-018	10.99	60.1
27.30	2.618e-018	10.99	60.1
27.40	2.584e-018	10.99	60.1
27.50	2.549e-018	10.99	60.1
27.60	2.516e-018	10.99	60.1
27.70	2.483e-018	10.99	60.1
27.80	2.450e-018	10.99	60.1
27.90	2.418e-018	10.99	60.1
28.00	2.387e-018	10.99	60.1
28.10	2.356e-018	10.99	60.1
28.20	2.326e-018	10.99	60.1
28.30	2.296e-018	10.99	60.1
28.40	2.266e-018	10.99	60.1
28.50	2.237e-018	10.99	60.1
28.60	2.209e-018	10.99	60.1
28.70	2.181e-018	10.99	60.1
28.80	2.153e-018	10.99	60.1
28.90	2.126e-018	10.99	60.1
29.00	2.099e-018	10.99	60.1
29.10	2.073e-018	10.99	60.1
29.20	2.047e-018	10.99	60.1
29.30	2.021e-018	10.99	60.1
29.40	1.996e-018	10.99	60.1
29.50	1.971e-018	10.99	60.1
29.60	1.947e-018	10.99	60.1
29.70	1.923e-018	10.99	60.1
29.80	1.899e-018	10.99	60.1
29.90	1.876e-018	10.99	60.1
30.00	1.853e-018	10.99	60.1
30.10	1.831e-018	10.99	60.1
30.20	1.809e-018	10.99	60.1
30.30	1.787e-018	10.99	60.1
30.40	1.765e-018	10.99	60.1
30.50	1.744e-018	10.99	60.1
30.60	1.723e-018	10.99	60.1
30.70	1.702e-018	10.99	60.1
30.80	1.682e-018	10.99	60.1
30.90	1.662e-018	10.99	60.1
31.00	1.642e-018	10.99	60.1
31.10	1.623e-018	10.99	60.1
31.20	1.604e-018	10.99	60.1
31.30	1.585e-018	10.99	60.1
31.40	1.566e-018	10.99	60.1
31.50	1.548e-018	10.99	60.1
31.60	1.530e-018	10.99	60.1
31.70	1.512e-018	10.99	60.1
31.80	1.495e-018	10.99	60.1
31.90	1.477e-018	10.99	60.1
32.00	1.460e-018	10.99	60.1
32.10	1.444e-018	10.99	60.1
32.20	1.427e-018	10.99	60.1
32.30	1.411e-018	10.99	60.1
32.40	1.395e-018	10.99	60.1
32.50	1.379e-018	10.99	60.1
32.60	1.363e-018	10.99	60.1
32.70	1.348e-018	10.99	60.1
32.80	1.333e-018	10.99	60.1
32.90	1.318e-018	10.99	60.1
33.00	1.303e-018	10.99	60.1
33.10	1.288e-018	10.99	60.1
33.20	1.274e-018	10.99	60.1
33.30	1.260e-018	10.99	60.1
33.40	1.246e-018	10.99	60.1
33.50	1.232e-018	10.99	60.1
33.60	1.219e-018	10.99	60.1

Wavelength (microns)	Irradiance (w/cm2/um)	Irradiance Uncertainty (%)	Variability (%)
33.70	1.205e-018	10.99	60.1
33.80	1.192e-018	10.99	60.1
33.90	1.179e-018	10.99	60.1
34.00	1.166e-018	10.99	60.1
34.10	1.154e-018	10.99	60.1
34.20	1.141e-018	10.99	60.1
34.30	1.129e-018	10.99	60.1
34.40	1.116e-018	10.99	60.1
34.50	1.104e-018	10.99	60.1
34.60	1.093e-018	10.99	60.1
34.70	1.081e-018	10.99	60.1
34.80	1.069e-018	10.99	60.1
34.90	1.058e-018	10.99	60.1
35.00	1.047e-018	10.99	60.1

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APPENDIX C

REDUCTION AND ANALYSIS OF CELESTIAL BACKGROUND EXPERIMENT CB01 - CHARACTERIZATION OF THE ZODIACAL BACKGROUND AT SMALL SOLAR ANGLES

C1. BACKGROUND

The aim of this analysis is to extract the zodiacal background signal from contaminated data of the celestial background experiment that was designed to measure the zodiacal flux close to the sun. The data consists scans at constant longitude that come as close as 25° from the sun. To achieve this solar elongation angle, the Earth was used as an occulting disk to block the thermal loading of the cryogenic sensor by the sun. This method of observation led to Non-Rejected Earth Radiance (NRER) contamination in the data.

An empirical model for the NRER has been developed at Vanguard Research. The model is also based upon the data obtained by MSX satellite as part of the data calibration experiment. The primary goal was to use this NRER model to correct for the contamination and thereby extract the zodiacal signal at small solar angles.

C2. OBSERVATIONS

In this experiment, each timeline or Data Collection Event (DCE) consisted of an ecliptic pole-to-pole scan. The scans maintained constant ecliptic longitude, which implied that the solar elongation or sun angle was changing continuously.

The near-sun observations of the zodiacal cloud consisted of five scans, each extending from the north ecliptic pole to the south ecliptic pole. The solar elongation was a minimum near the ecliptic plane. The following table C1 provides the observational parameters for each scan. All the scans maintained constant ecliptic longitude resulting in the variation of elongation with ecliptic latitude.

Table C1. List of ecliptic longitudes and Solar Elongation ranges for CB01 scans.

Scan No.	Ecliptic Longitude of Observation	Ecliptic Longitude of Sun	Range of Solar Elongation	Range of Ecliptic latitudes
1	93.3°	118.4°	25°-90°	-90° to 90°
2	108.4°	134.4°	26°-90°	-90° to 90°
3	108.3°	136.7°	27°-90°	-90° to 90°
4	110.3°	138.2°	28°-90°	-90° to 90°
5	109.0°	134.4°	29°-90°	-90° to 90°

C3. DATA REDUCTION & ANALYSIS

The data reduction was carried out as follows.

a) The '*cb01*_geo.dat*' files provided with the DBFGEN files for CB01 contains the attitude information, including the roll angle and coordinates of the spacecraft. This was used to determine the variation of tangent height of the line-of-sight of the spacecraft as a function of ecliptic latitude. The data is interpolated to the match the larger number of data samples of the DBFGEN file containing the radiance measurements. The output from this calculation is a set of tangent heights and roll angles for every sample in the DBFGEN file.

b) The NRER model is a three dimensional model that gives the Earth radiance as a function of tangent height and roll angle of the line-of-sight. The output data after processing the 'geo' file was used to parse the three-dimensional array and extract the corresponding NRER value.

c) NRER Subtraction Procedure:
The first step was to subtract the NRER contribution, predicted by the model, from the DBFGEN profile. There was a significant residual implying that the model radiance had to be scaled higher depending upon the waveband and the DCE. The scale factor was determined using the following iterative process.
   - An initial guess for the scale factor was used to scale the model radiance of NRER and subtract it to yield the first estimate of the zodiacal profile.
   - Then, the latitude of the peak of the zodiacal profile was determined.
   - The zodiacal profile was assumed to be symmetrical about the location of the peak radiance, which is a reasonable assumption, as the zodiacal is symmetric about a plane that is different from the Ecliptic. Therefore, the southern half of the profile, free of NRER contamination, was used to estimate the zodiacal signal for the contaminated northern half of the profile.
   - The uncontaminated zodiacal profile was subtracted from the observations (DBFGEN profile) and the remainder was attributed to NRER.
   - After the NRER was estimated from the observations, the ratio of the observed radiance to that calculated from the model was calculated. The average value of this ratio is first estimate of the scale factor for modifying the model NRER.
   - To obtain the final scale factor, the above process was iterated by using the scale factor determined in the first iteration as the guess value for the second iteration. When the input scale factor is equal to the output scale factor the solution converged to a single value. Table 1 lists the scale factors for all the CB01 profiles that have been analyzed.
   - When the final scale factor has been determined, the scaled NRER flux is subtracted from the DBFGEN file to yield the zodiacal background.

This method was effective for most of the DCEs except CB01_03. In CB01_03, the NRER contamination is very close to the peak of the zodiacal signal, making the initial location of the peak of the zodiacal cloud difficult to determine. The iteration method yielded an asymmetric zodiacal profile. Therefore, the scale factor was estimated by trial and error to maximize the symmetry of the zodiacal profile.

d) The final step was to smooth the profile with a simple boxcar average of the data when plotted against the latitude. The window width was 201, which was settled on after testing with various widths to minimize the noise without losing the structure. The smooth profile was also stored as a data product.

e) There is another residual that emerges after the smoothing process at higher north ecliptic latitudes. This occurs at nearly the same location in each band and may be caused by the uncertainty in the smooth NRER model.

Table C2: Scaling factors for NRER

DCE → Waveband	03	07	08	09	10
A	1.30	1.29311	1.32964	1.36717	1.39423
C	1.36	1.36496	1.41531	1.45419	1.57898
D	1.10	1.10486	1.13109	1.13537	1.25659
E	1.05	1.07829	1.11870	1.09833	1.18149

C4. DATA PRODUCTS ON CDROM

There are two primary data products:
a) <DCE>_<waveband>_dbh_nrer.dat
b) <DCE>_<waveband>_dbh_zod.dat

The file types listed above have the same format as the input DBFGEN file. In a) the total observed radiance was replaced by the NRER estimate (including the scaling factor and in b) lists the zodiacal signal after NRER subtraction.

Secondary data products are as follows:
c) <DCE>_<waveband>_smooth_zod.dat
d) cb01<DCE>_<waveband>_nrer.gif

The file in c) contains two columns of data, where column 1 is the ecliptic latitude (from column 4 of the DBFGEN file) and column 2 has the smoothed zodiacal radiance obtained by boxcar average of the data in file b) with a window of 201.

The final file type d) is a gif image of the smooth zodiacal profile estimated by this process.