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ARTIFACTS AT 4.5 AND 8.0 MICRONS IN SHORT-WAVELENGTH SPECTRA FROM THE *INFRARED SPACE OBSERVATORY*[1]

S. D. Price,[2] G. C. Sloan,[3,4] and K. E. Kraemer[2,5]

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ABSTRACT

Spectra from the Short-Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* exhibit artifacts at 4.5 and 8 μm. These artifacts appear in spectra from a recent data release, OLP 10.0, as spurious broad emission features in the spectra of stars earlier than approximately F0, such as α CMa. Comparison of absolutely calibrated spectra of standard stars to corresponding spectra from the SWS reveals that these artifacts result from an underestimation of the strength of the CO and SiO molecular bands in the spectra of sources used as calibrators by the SWS. Although OLP 10.0 was intended to be the final data release, these findings have led to an additional release addressing this issue, OLP 10.1, which corrects the artifacts.

Subject headings: astronomical data bases: miscellaneous — methods: data analysis — techniques: spectroscopic

1. INTRODUCTION

The Short-Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* (*ISO*) obtained approximately 1250 spectra covering the full 2.4–45 μm wavelength range at moderate resolution. We are engaged in an ongoing project to classify these spectra (Kraemer et al. 2001), reprocess them, and present them in a publicly available on-line database (G. Sloan et al. 2002, in preparation). SWS data are currently available in a partially processed form called Auto-Analysis Results (AARs). The AARs have a fairly complex format (Leech et al. 2001)[6] that requires further processing before the data can be used for scientific analysis. Our processing method reduces these data to a single continuous 2.4–45 μm spectrum.

In assessing the quality of our new reprocessing algorithm, we compared the results for several infrared standards observed with the SWS to absolutely calibrated spectra from Cohen et al. (1992a, 1995, 1996a, 1996b; Cohen, Walker, & Wittborn 1992b; M. Cohen et al. 2002, in preparation). These standards are based on synthetic spectra of the A0 dwarf α Lyrae and the A1 dwarf α CMa, which serve as the reference standards in the system. Cohen et al. (1992a) describe the details of their method, which used high-quality ground-based and airborne photometry to normalize the synthetic spectra to measured astronomical fluxes. The synthetic spectra are based on the models of Kurucz (1979), with updated opacities and metallicities (Castelli & Kurucz 1994).

Secondary standards are added to the system by observing their spectra in conjunction with those of the primaries so that atmospheric, telescopic, and instrumental transients can be removed. The spectra for the secondary standards are then obtained by dividing the observed secondary by the observed reference standard and multiplying by the assumed spectrum (the model) for the reference, degraded to match the spectral resolution of the instrument used:

$$S_{b,\,\mathrm{final}}(\lambda) = \frac{S_{b,\,\mathrm{obs}}(\lambda)}{S_{a,\,\mathrm{obs}}(\lambda)} S_{a,\,\mathrm{assumed}}(\lambda), \qquad (1)$$

where the subscript a refers to the reference standard and the subscript b refers to the secondary. This is the standard method used by spectroscopists at ground-based telescopes to calibrate a program source by ratioing its spectrum to that of a standard star, preferably secured at an air mass matching that of the target. In effect, equation (1) transfers the quality of the synthetic A star model from the reference to the new standard, whatever its spectral type.

Cohen et al. (1992b, 1995, 1996a, 1996b, 2001) have applied this method to create absolutely calibrated composite spectra for 13 infrared standards, using spectra from ground-based telescopes, the Kuiper Airborne Observatory (KAO), and the *Infrared Astronomical Satellite* (*IRAS*; further details of the process can be found in Cohen et al. (1992a, 1992b). Cohen et al. (1996a) added α^1 Cen (G2 V) as an alternative reference standard for the southern hemisphere to give a total of three reference standards in addition to the 13 secondaries. Most of the secondary standards are giants with spectral classes later than K0 and were chosen for their intrinsic brightness; sources later than approximately M3 are avoided because of the possibility of their variability (Eyer & Grenon 1997).

The preferred infrared reference standard is Sirius (α CMa) because of its brightness and its dust-free spectrum beyond 20 μm. Figure 1 compares our derived SWS spectrum of this source to the Kurucz model presented by Cohen et al. (1992a). Deviations between the two occur in the vicinity of 4.5 μm and again at 8.0 μm. In this Letter we propose an explanation for the origin of this discrepancy and discuss the implications for the calibration of the SWS database and the impact on calibration of future infrared missions.

2. DATA FORMAT AND ANALYSIS

Data from the SWS are publicly available in AAR format. This format corrects the spectra, as far as possible, for the

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[2] Air Force Research Laboratory, Space Vehicles Directorate, 29 Randolph Road, Hanscom AFB, MA 01731; steve.price@hanscom.af.mil, kathleen.kraemer@hanscom.af.mil.

[3] Institute for Scientific Research, Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA 02467; sloan@ssa1.arc.nasa.gov.

[4] Infrared Spectrograph Science Center, Cornell University, Ithaca, NY 14853.

[5] Institute for Astrophysical Research, Boston University, Boston, MA 02215.

[6] See http://www.iso.vilspa.esa.es/manuals/HANDBOOK/VI/sws_hb.

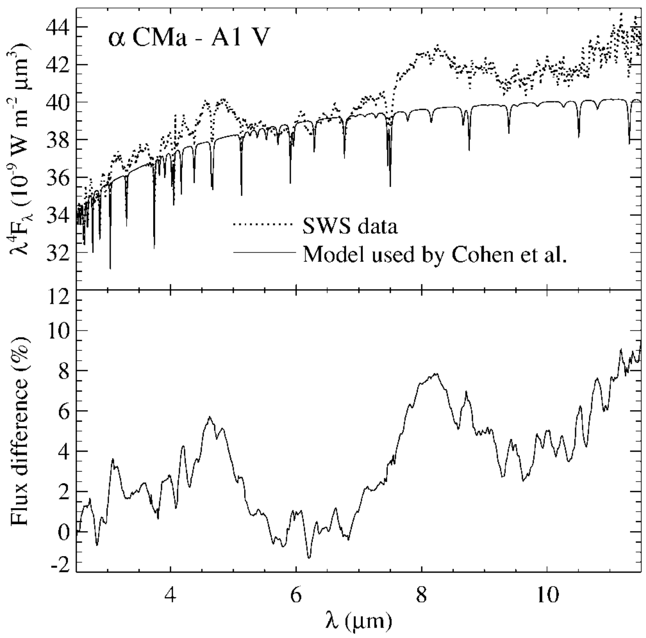

FIG. 1.—*Top*: Comparison of SWS data for α CMa (*dotted line*) with the Kurucz model used by Cohen et al. (1992a; *solid line*). The spectra have been normalized between 6 and 7 μm and are plotted in units of $\lambda^4 F_\lambda$, which clearly shows deviations from the reference spectrum at the CO and SiO bands. *Bottom*: The difference between the two as a percentage of the flux density of the Kurucz model.

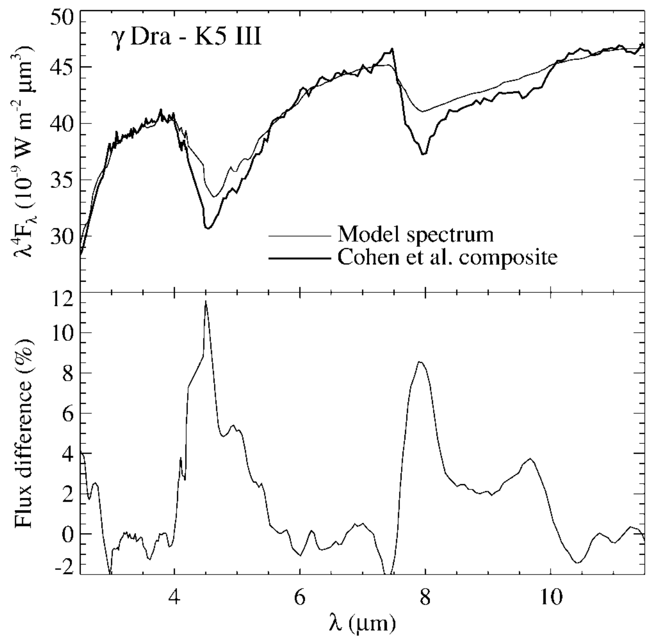

FIG. 2.—Comparison between the model of γ Dra used to calibrate the SWS data (*thin line*) and the composite spectrum calibrated by Cohen et al. (1996b; *thick line*). The spectra have been normalized between 6 and 7 μm and the model resampled to match the composite. The data for the model have been adapted from Figs. 8 and 9 in Decin (2002).

relative spectral response of the detectors, differences in gains between individual detectors, and a variety of other issues, as described by Leech et al. (2001). The files are organized in 12 spectral segments, ranging from one to four for each of the four different detector bands. Each spectral segment contains interleaved spectra from the 12 individual detectors, scanned in the direction of both increasing and decreasing wavelength, giving a total of 24 separate spectra for each spectral segment. Thus, the processing of the full wavelength range from an AAR file requires the combination of 288 individual spectra into one.

We start with data from the Off-Line Processing (OLP) pipeline 10.0, made available in 2001 June, which was intended to be the final release. This version includes the latest attempts to remove the memory effect from the Si : As data (4–12 μm; Kester, Fouks, & Lahuis 2001). Although these attempts have significantly improved the data, residual effects remain, and one can see that the spectra presented here tend to diverge from the expected result as the data approach 12 μm. However, we have high confidence in the quality of the data at shorter wavelengths, where the flux levels from the sources are much stronger and where the discrepancies between the SWS data and the reference spectra occur.

G. Sloan et al. (2002, in preparation) will present details of the algorithm used to combine the 288 individual spectra into one. We have tested for the possibility that the algorithm might be responsible for the artifacts seen in Figure 1 by processing the AAR data manually with the Infrared Spectral Analysis Package following the standard procedures. The two methods produce similar results, which indicates that the problem is intrinsic to the spectrum released by *ISO* and not to a specific method of processing. The artifact peaking at 4.5 μm also appears in Figures 6 and 7 of Decin (2002), although the wavelength stretch makes it more difficult to notice.

3. DISCUSSION

The divergence between the SWS spectrum of α CMa and the Kurucz model is characterized by two broad "emission" features, at ~4–5 and ~8 μm. (The rise at longer wavelengths is caused by the memory effect mentioned in § 2.) The feature at 8 μm is reminiscent of the 8 μm emission artifact found in the data from the Low Resolution Spectrometer (LRS) aboard *IRAS* by Cohen et al. (1992b). The LRS database was originally calibrated assuming that α Tau could be characterized as a 10^4 K blackbody. However, since the spectrum of α Tau (a K5 III star) contains significant absorption from the SiO fundamental band at 8 μm, this error propagated to the entire LRS database, producing an apparent emission feature in the spectra of α CMa, α Lyr, and other early-type stars.

Fifteen stars have served as spectral calibrators for the SWS (Schaeidt et al. 1996; Leech et al. 2001; Shipman et al. 2001). Ten of them are K and M giants, which show strong molecular absorption bands in their spectra. The dominant bands peak at wavelengths of ~2.4 μm (CO overtone), ~4.1 μm (SiO overtone), ~4.5 μm (CO fundamental, blended with the weaker SiO overtone), and ~8.0 μm (SiO fundamental). For the assumed spectrum of each of these stars in OLP 10.0, the SWS instrument team chose to use synthetic models of the stars from 2 to 12 μm. For longer wavelengths, a composite spectrum from Cohen et al. (1992a, 1995, 1996a, 1996b; Cohcen Walker, & Witteborn 1992) was available or a template spectrum from Cohen et al. (1999), where no composite existed, were used. The two sets of data were spliced together at 12 μm (Schaeidt et al. 1996; Leech et al. 2001; Shipman et al. 2001). Previous pipeline releases used the Cohen composites and templates for the entire wavelength range.

The K5 giant γ Dra is a typical example of an SWS calibrator. Figure 2 compares the synthetic spectrum of this source (Decin 2000, 2002) to the observationally calibrated composite spec-

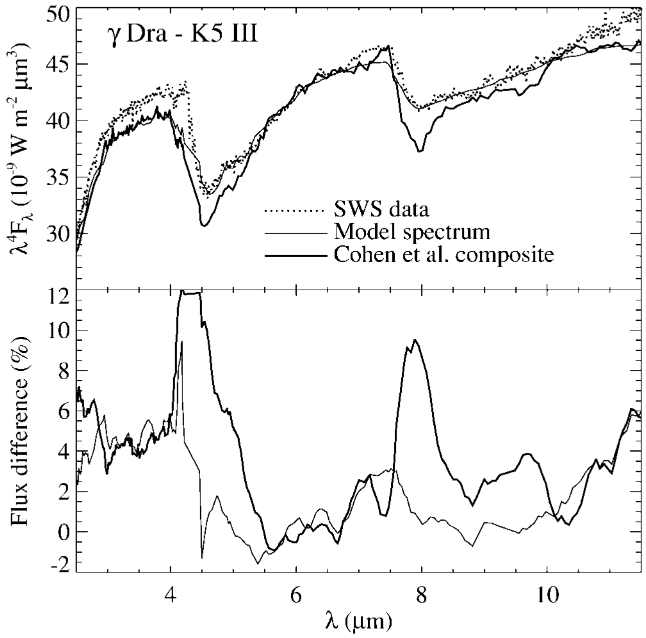

FIG. 3.—Comparing SWS data for γ Dra (*dotted line*) with calibrator spectra. *Top*: Same as in Fig. 2, but with a spectrum from the SWS superposed (*dotted line*). *Bottom*: The difference between the SWS data and the model (*thin line*) to the difference between the SWS data and the composite from Cohen et al. (1996b; *thick line*).

trum (Cohen et al. 1996b). The differences between the two spectra (*lower panel*) are similar to the artifacts seen in Figure 1. Decin (2002) compares the composite spectra of several other SWS calibrators to the synthetic spectra (in her Fig. 9), and most of them show similar deviations.[7] It is highly unlikely that an instrumental effect (such as the memory effect) would manifest itself precisely at the wavelengths of these photospheric absorption bands.

The coincidence of the emission artifacts apparent in Figure 1 with the molecular bands in K and M stars and the similarity of the artifacts to the deviations between the model and the composite spectrum in Figure 2 lead us to hypothesize that the artifacts result from an underestimate of the depth of these bands in the synthetic spectra.

Figure 3 compares the data from the SWS to both the model and composite spectrum of γ Dra. Although not perfect, *the SWS spectrum, as calibrated in OLP 10.0, matches the model of γ Dra significantly better than the Cohen composite*. Additional spectra of γ Dra from the SWS database, taken at different times during the mission and at different spectral resolutions, as well as spectra of other cool calibrators, produce similar results.

If the synthetic spectra used to calibrate the SWS generally underestimate the strength of the molecular bands, then this miscalibration should propagate to the entire SWS database. As Figure 4 shows, the artifacts at 4.5 and 8 μm are readily seen in bright spectra from early-type stars, including the reference standard α Lyr, which should show neither emission nor absorption from molecular bands. In the spectrum of the average giant with no composite spectrum for comparison, the effect of the miscalibration will be more subtle and more difficult to recognize, since it will reduce only the apparent depth of the absorption bands.

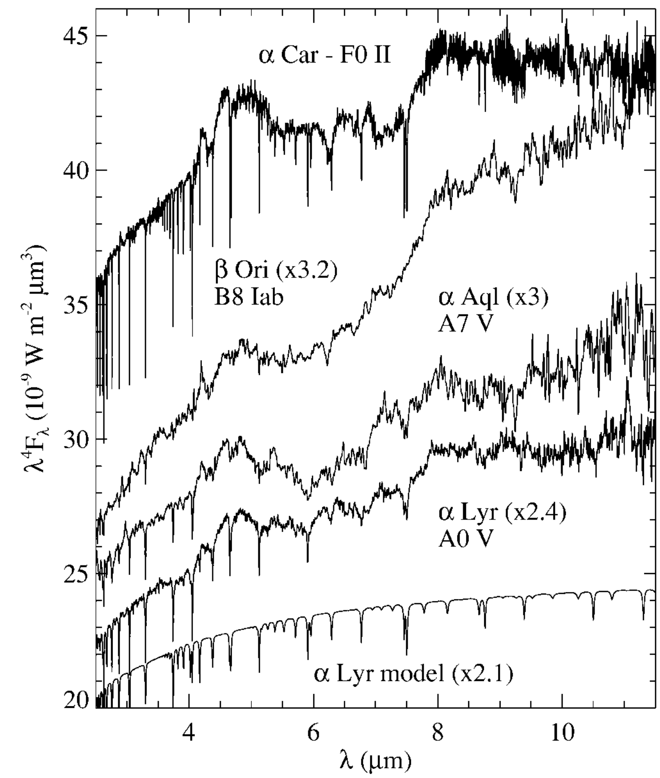

FIG. 4.—Several SWS spectra of bright early-type naked stars. Most have been multiplied by a constant (given in parentheses). The bottom spectrum is the Kurucz model of α Lyr used by Cohen et al. (1992a).

In Figure 3 the difference between the SWS data and the composite spectrum for γ Dra exhibits the largest excess between ~4.0 and 4.7 μm. While an excess clearly exists at these wavelengths in the spectra of the hot stars in Figure 4, the confidence level of the magnitude of this excess shown in Figure 3 is not high. Because the atmosphere is almost opaque in the core of the CO_2 band at 4.3 μm, even at aircraft altitudes, the uncertainty in the spectral composite is typically ~6% from 4.22 to 4.58 μm and peaks at 10% at 4.22 μm (Cohen et al. 1996b). Roughly half of the composites, including γ Dra, have a data gap at ~4.2–4.4 μm due to the atmospheric band. The spectral artifact is, however, much broader than the data gap and larger than the uncertainties can account for. The uncertainties in the composite spectrum at the other feature are $\lesssim$2%.

To reduce the noise from a single comparison, we calculated the weighted average of the ratios of all of the spectra common between the sources used to spectroscopically calibrate the SWS and the composite and reference spectra from Cohen et al. This weighted mean, displayed in Figure 5, provides an estimate for the modifications needed in the OLP 10.0 data. It also provides an assessment of the reliability of the synthetic spectra relative to the absolutely calibrated composite spectra.

In light of our findings, the SWS team have revised their calibration strategy and the *ISO* Data Center has agreed to an additional data release, OLP 10.1. By basing the new spectral calibration only on stars earlier than K, the worst of the dis-

[7] Decin (2001) notes the discrepancy between the model and the composite spectrum of γ Dra, but incorrectly attributes it to the substitution of data of α Tau for γ Dra in this wavelength regime. In the header to the file containing the composite spectral data for γ Dra, Cohen et al. (1996b) state that they calibrated this spectral region using spectral ratios of γ Dra to α Boo obtained at the KAO.

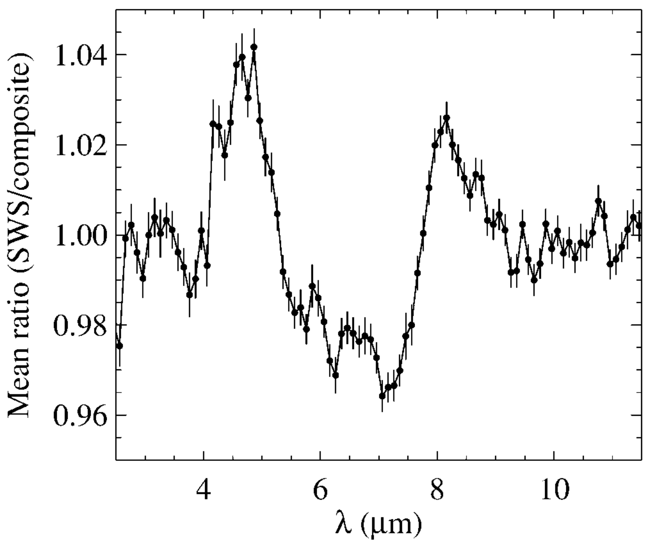

FIG. 5.—Weighted mean of the deviations between the SWS spectra of the standard stars in common with the composites and models of Cohen et al. Both the SWS data and the composites were resampled to 0.1 μm spacing and placed on the same wavelength grid. Error bars are 1 σ.

crepancy between the synthetic spectra and the Cohen spectra should be mitigated. The Decin models agree with the Cohen composites, templates, or Kurucz models (as appropriate) for the five stars (two A stars, one F star, and two G stars) that meet this criterion (R. Shipman 2001, private communication).

4. CONCLUSIONS

We have identified spectral artifacts in the vicinity of the CO and SiO bands of late-type standard stars that appear in all OLP 10.0 spectra. These artifacts constitute a known systematic bias over a fairly large spectral range, and removing them is relatively straightforward. While OLP 10.0 was to have been the final version, an additional release, OLP 10.1, has been made to correct the database based on our findings.

The SWS calibrations between 2 and 12 μm were predominantly based on stellar atmospheric models of cool stars. These models have been used with great success in analysis of physical properties of cool stars (e.g., Decin et al. 2000). Model spectra of A stars, which contain only atomic lines and no molecular bands, appear to be well founded. Synthetic spectra can also achieve higher spectral resolution than that afforded by the composites. However, the artifacts in the SWS database that mirror the dominant molecular absorption features in the 4–10 μm range indicate that synthetic spectra of cool giants require further progress before they can be used for definitive spectral calibration.

The Infrared Spectrograph (IRS) on the upcoming Space Infrared Telescope Facility faces issues similar to those encountered by the SWS team, with the added complication that all of the commonly used spectral standards will be far too bright for use on the IRS. Until the commission of the Stratospheric Observatory for Infrared Astronomy, it will prove difficult to observationally calibrate standards faint enough for use by the IRS. Until this happens, the IRS will need to rely on models for spectral calibration. If models of later stars are required, improvements in the production of synthetic spectra will also be necessary.

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