



The Extended Atlas of Low-resolution Spectra from the Infrared Astronomical Satellite

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Abstract

We present an updated atlas of spectra from the Low-Resolution Spectrometer (LRS) on the Infrared Astronomical Satellite (IRAS), which took spectra from 7.67 to 22.73 μm with a spectral resolving power ($\lambda/\Delta\lambda$) of 20–60. The updated atlas includes 11,238 spectra, including 5425 spectra published in the original LRS Atlas, 5796 spectra published in three later papers, and 17 spectra previously available online but not published. The updated atlas has significantly more sources close to the Galactic plane than the original atlas. We have applied an improved spectral correction to remove an artifact at 8 μm in the original database. While the IRAS mission flew over 40 yr ago, the extended LRS atlas remains the single most complete database of mid-infrared spectra of nearby and bright objects in the Galaxy.

Unified Astronomy Thesaurus concepts: [Infrared spectroscopy \(2285\)](#)

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1. Introduction

The Infrared Astronomical Satellite (IRAS) revolutionized infrared astronomy. Launched on 1983 January 26, IRAS was a 0.57 m infrared space telescope that surveyed nearly the entire sky until it exhausted its cryogenics on 1983 November 22. The main focal-plane array included 59 discrete functioning detectors sensitive to radiation in four photometric bands: 12, 25, 60, and 100 μm (G. Neugebauer et al. 1984; C. A. Beichman et al. 1988).

The photometry led to multiple catalogs, most notably the Point Source Catalog (PSC) with nearly 250,000 sources (G. Neugebauer et al. 2019). Prior to the IRAS mission, the most complete infrared catalogs were the ground-based Two-Micron Sky Survey (TMSS; G. Neugebauer & R. B. Leighton 1969), with 5412 sources between declinations of -33 and $+81$, and the Air Force Geophysics Laboratory (AFGL) rocket survey (S. D. Price & R. G. Walker 1976), with 2363 sources at 4, 11, 20, and 27 μm .⁴ These statistics show how IRAS significantly improved the sky and wavelength coverage of previous surveys and dramatically increased the number of sources known, by a factor of ~ 50 –100. Except for the crowded Galactic plane and a couple of gaps in coverage, the IRAS PSC is reasonably complete down to ~ 0.5 Jy at 12 μm .

In addition to the photometric data arrays, IRAS also flew with a Low-Resolution Spectrometer (LRS) that obtained spectra from 7.67 to 22.73 μm . The LRS Atlas, published soon after the mission, contained spectra of 5425 sources (F. M. Olnon et al. 1986). To this day, this database represents the most complete spectral survey of the brightest objects in the mid-infrared sky. Just as post-main-sequence objects dominate the population observed by the TMSS

(G. L. Grasdale & J.E. Gaustad 1971), they also dominate the LRS Atlas (F. M. Olnon et al. 1986; P. Hacking et al. 1985). Such is the nature of the infrared sky. Thus, the LRS Atlas provides an unsurpassed opportunity to spectroscopically study dying stars and the dust they produce within the Galaxy.

Many revelations about evolved stars and circumstellar dust followed the publication of the LRS Atlas. For example, the LRS spectra revealed the presence of dust components in addition to amorphous silicates in the dust shells around oxygen-rich stars on the asymptotic giant branch (AGB; I. R. Little-Marenin & S. D. Price 1986; I. R. Little-Marenin & S. J. Little 1990), which led to the identification of amorphous alumina (T. Onaka et al. 1989) and crystalline alumina (W. Glaccum 1995; A. Takigawa et al. 2015). Another example is the discovery of molecular SiO absorption at ~ 8 μm in the atmospheres of K giants (K. Volk & M. Cohen 1989b; M. Cohen et al. 1992a, 1992b), which resulted in a calibration artifact in the entire LRS Atlas and would impact the calibration of infrared spectrometers on the Infrared Space Observatory (ISO; S. D. Price et al. 2002) and the Spitzer Space Telescope (G. C. Sloan et al. 2015). These highlights are just two examples among many.

This science resulted from the 5425 spectra in the original LRS Atlas, but the LRS database includes a great deal more spectral data. As F. M. Olnon et al. (1986) explained, the full database contained 170,000 spectra of 50,000 sources, but the published atlas included spectra for only $\sim 10\%$ of the sources. Their most stringent criterion was that a source had to have two complete spectra in the multiple scans covering each part of the sky. Most bright stars outside of the Galactic plane passed that test, and F. M. Olnon et al. (1986) estimated that the LRS sample was $\sim 90\%$ complete down to 28 Jy at 12 μm (i.e., zero magnitude) at high Galactic latitudes. Even then, they noted that “some very bright red stars are conspicuously absent,” singling out α Ceti (Mira) and R Leo.

Consequently, others looked to the raw database for missing sources. K. Volk & M. Cohen (1989a) extracted the spectra of 356 additional sources brighter than 40 Jy at 12 μm from the IRAS database (including Mira and R Leo). They concluded

⁴ The sky coverage of the AFGL rocket survey depended on the wavelength.



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that no additional spectra of point sources brighter than that limit could be extracted. The next step was to go fainter. K. Volk et al. (1991) added 486 more sources with flux densities at $12\ \mu\text{m}$ between 20 and 40 Jy. Finally, S. Kwok et al. (1997) published an extended atlas of spectra of 11,224 sources (i.e., another 4957 previously unpublished sources). For years, these spectra were accessible from a server hosted at the University of Calgary, but when that server went offline, the extended atlas ceased to be available to the general public.

Our objective is to improve the extended atlas of spectra from the LRS on IRAS and make those data available once again to the community. As new missions like the James Webb Space Telescope obtain spectra of individual stars in galaxies across the Local Group and, for bright supergiants, even from nearby groups of galaxies, the extended LRS atlas can serve as a powerful comparison sample of infrared spectra from our own Galaxy.

Section 2 describes the sample and data processing and investigates the photometric accuracy of the spectra in the LRS database. Appendix A provides details on the inclusion and exclusion of spectra from different atlases. Section 3 assesses the spectral accuracy and the need for a spectral correction, while Appendix B explains in more detail how that correction was determined. Section 4 looks at the completeness of the new extended LRS atlas, and Section 5 summarizes the key points that users of the new database should keep in mind. Appendix C describes the infrared spectral classifications that can help users navigate the database, and Appendix D explains how to access the new atlas and how the data files are organized.

2. The Extended LRS Atlas

2.1. Sample

The sample presented here is based on the sample on the server at the University of Calgary, with some modifications. It includes all 5425 sources in the LRS Atlas (F. M. Olmon et al. 1986). Those sources are referred to here as the “original” sample. It also includes all 356 spectra brighter than 40 Jy at $12\ \mu\text{m}$ added by K. Volk & M. Cohen (1989a), all but one of the 486 spectra with flux densities at $12\ \mu\text{m}$ between 20 and 40 Jy added by K. Volk et al. (1991), and 4955 of the 4957 sources added by S. Kwok et al. (1997). Together, these three groups of spectra are referred to as the “supplemental” sample. Finally, the present sample also contains 17 additional spectra on the University of Calgary server but not included by S. Kwok et al. (1997); these are the “extra” sources. Appendix A provides details of sources that have been rejected or renamed and the reasons why.

2.2. Data Processing

The LRS was an objective-prism spectrometer that dispersed light from targets in the scan direction as the spacecraft surveyed the sky. The lack of a slit means that the spectral resolution is low, especially for extended sources. The large beam size of the telescope and scanning design meant that many spectra could not be recovered in crowded fields. Different detectors simultaneously obtained the blue and red spectral segments, covering $7.67\text{--}13.45\ \mu\text{m}$ and $10.6\text{--}22.7\ \mu\text{m}$, respectively. Figure 1 illustrates the spectral resolution of the instrument, plotting the full width at half-maximum of the resolution element ($\Delta\lambda$) as a function of wavelength. These

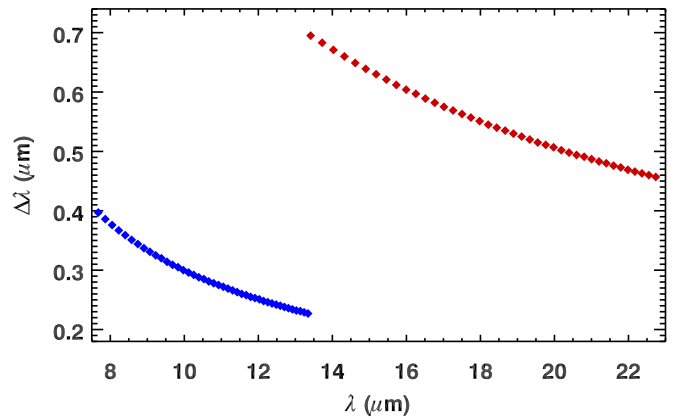


Figure 1. The resolution element ($\Delta\lambda$) as a function of wavelength for the blue and red segments of the LRS at each wavelength in the standard LRS wavelength grid.

values were determined from the plot of spectral resolving power ($R \equiv \lambda/\Delta\lambda$) versus wavelength in Chapter IX of the Explanatory Supplement (C. A. Beichman et al. 1988). The spectral resolving power varied from ~ 20 at the short-wavelength end of each segment to ~ 60 at the long-wavelength end.

All of the original spectra in the LRS Atlas (F. M. Olmon et al. 1986) were placed on a wavelength grid with two grid points per resolution element at $7.67\ \mu\text{m}$, smoothly increasing to 2.5 at $22.73\ \mu\text{m}$. The two segments were normalized multiplicatively using the overlap region, with the segment with more flagged data shifted to match the other. Multiple spectra for a given target were averaged together. The supplemental spectra from K. Volk & M. Cohen (1989a), K. Volk et al. (1991), and S. Kwok et al. (1997) and the extra spectra on the Calgary server followed the same processing steps as the original atlas.

The spectra presented here are processed in much the same way as before, but with two changes. First, the spectra were trimmed, so that the blue segment includes 43 wavelength elements from 7.67 to $13.45\ \mu\text{m}$ and the red segment includes 41 wavelength elements from 13.41 to $22.73\ \mu\text{m}$. The trimming involved removing a data point at $22.92\ \mu\text{m}$ because of its unreliability. Second, the spectra were corrected for the SiO artifact present in previously published spectra. This artifact arose because the assumed truth spectra for K giants used as spectral standards omitted the SiO fundamental absorption band at $8\ \mu\text{m}$, which was first noted by K. Volk & M. Cohen (1989b). Figure 2 gives an example of the SiO artifact in the star α CMi (Procyon, F5 IV–V). The comparison spectrum is a BOSZ model with $T_{\text{eff}} = 6500\ \text{K}$, $\log g = 4.0$, and solar abundances (R. C. Bohlin et al. 2017; S. Mészáros et al. 2024),⁵ scaled to the LRS spectrum at $12\ \mu\text{m}$. To remove the spectral artifact at $\sim 8\ \mu\text{m}$, we rederived the correction originally developed by M. Cohen et al. (1992a), as described below (Section 3 and Appendix B).

2.3. Photometric Accuracy of the LRS

Comparing the $12\ \mu\text{m}$ flux densities of sources in the LRS Atlas with the values in the PSC reveals a discrepancy that depends on the brightness of the source. Figure 3 shows this shift for the dust-free stars with LRS characterizations of 18,

⁵ <https://archive.stsci.edu/hlsp/bosz>

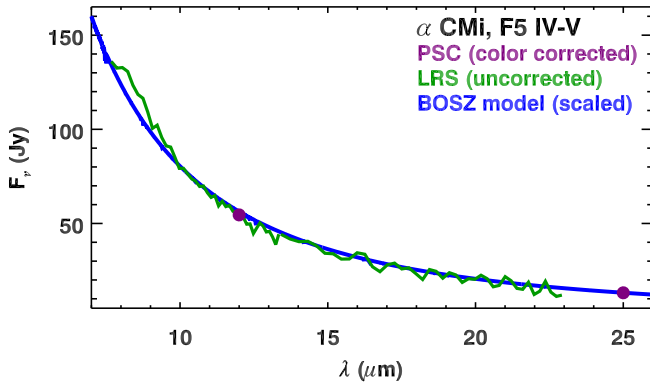


Figure 2. The uncorrected LRS spectrum of Procyon (α CMi), compared to a scaled BOSZ model and the photometry from the PSC. The LRS spectrum shows the emission artifact at 8–11 μm in the original LRS Atlas.

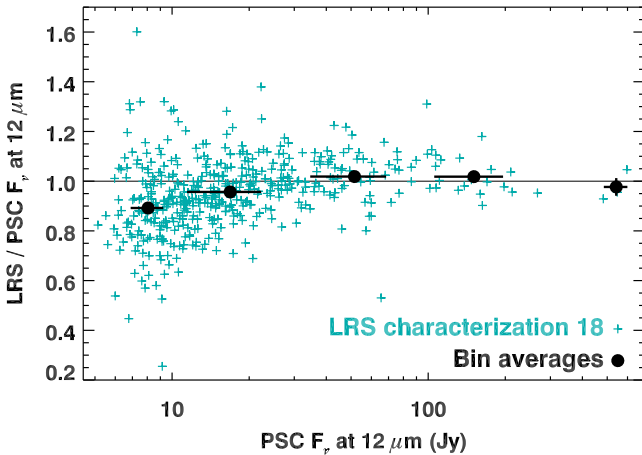


Figure 3. The ratio of the flux density at 12 μm of the dust-free stars in the LRS Atlas from the spectra over the color-corrected photometry from the IRAS PSC. The large black circles give the averages in each half-decade bin, with horizontal error bars indicating the standard deviation and vertical error bars indicating the uncertainty in the mean. The vertical standard deviation is apparent from the spread in the individual data.

which indicates that they all have a Rayleigh–Jeans tail in the LRS wavelength regime.⁶ Dust-free stars have a range of color corrections in the 12 μm filter, from 1.41 to 1.47, depending on their effective temperature. We adopted a correction of 1.45, appropriate for a 10,000 K photosphere or a K giant with continuum opacity from the H^- ion (e.g., C. W. Engelke 1992). At worst, the uncertainty in color correction leads to a 3% uncertainty in the flux density at 12 μm . To determine the 12 μm flux from the LRS, the spectra were averaged from 11.8 to 12.2 μm in Rayleigh–Jeans units ($\lambda^2 F_\nu$) and then converted to Jy.

Table 1 gives the mean flux densities and flux ratios at 12 μm for the bins plotted in Figure 3. Above ~ 10 Jy the LRS/PSC ratios are consistent with 1.0, but for fainter targets the scatter in the ratio LRS/PSC grows quite large, and the mean of the distribution tails off, reaching a mean discrepancy of 10% in the faintest bin. The majority of the sources with spectra from the LRS are in the faintest two bins. For these fainter targets, either the PSC is not reliable or the LRS is not spectrophotometrically calibrated (or both). The downward trend in the mean ratio LRS/PSC as the sources grow fainter is

Table 1
Average Flux Densities at 12 μm

$\langle F_\nu \text{ at } 12 \mu\text{m} \rangle$ from PSC (Jy) ^a	$\langle \text{LRS/PSC at } 12 \mu\text{m} \rangle$ ^b	N
8 ± 1	0.89 ± 0.02	129
17 ± 5	0.96 ± 0.01	236
52 ± 17	1.02 ± 0.01	72
151 ± 45	1.02 ± 0.02	20
542 ± 57	0.98 ± 0.04	3

Notes.

^a Color corrected; uncertainties are standard deviations (1σ).

^b Uncertainties are uncertainties in the mean.

consistent with a slight oversubtraction of the background in the LRS data, but that hypothesis has not been confirmed.

Figure 3 raises questions about the photometric calibration of the IRAS PSC and/or the LRS. We have also investigated the calibration of the LRS by comparing the LRS spectra of bright infrared standard stars to spectra from other telescopes, starting with the sample of 13 bright red giants from G. C. Sloan et al. (2015, their Table 1). For each source, C. W. Engelke et al. (2006) produced a carefully calibrated spectrum, in most cases based on the spectrum from the Short-Wavelength Spectrometer (SWS; K. Leech et al. 2003), modified to align with the photometric calibration of the Midcourse Space Experiment (MSX; S. D. Price et al. 2004). When SWS data were unavailable, infrared spectra from other sources with similar spectral types were used. We will refer to these spectra based primarily on the SWS and MSX as the Hanscom spectra.⁷

We measured the 12 μm flux density of each source in the LRS and Hanscom spectra over the 11.8–12.2 μm range as for the comparison of the LRS and PSC above. Table 2 presents the results and the ratios of the LRS to the Hanscom spectrum. Excluding μ UMa, which is a clear outlier (and, probably not coincidentally, the faintest of the 13 standards), the mean ratio of LRS/Hanscom is 1.129 ± 0.026 , where the uncertainty is the uncertainty in the mean. That is a significant offset, but we have not corrected the extended LRS atlas to remove it. The previous comparison of the spectra from the LRS to the PSC revealed significant scatter in the ratio of the 12 μm flux densities for dust-free stars and a decrease in that ratio for fainter targets. These issues suggest that photometrically calibrating the entire database is not possible. Consequently, users of the database should keep in mind the potential issues with the absolute flux calibration.

3. Spectral Accuracy of the LRS

While we have not changed the absolute photometric correction of the LRS data, we have applied a spectral correction from 7.67 to 10.6 μm . Figure 2 illustrates the SiO artifact in that wavelength range, but plotting the spectra in F_ν units hides the details. Figure 4 examines the spectra of two well-known stars in Rayleigh–Jeans units, so that the Rayleigh–Jeans tail of the Planck function will appear as a horizontal line and any deviations are readily apparent. One of the standards is the A dwarf α CMa (Sirius), which has now replaced α Lyr (Vega) as the primary standard star for all UV–optical–infrared wavelengths (e.g., G. H. Rieke et al. 2023).

⁷ These spectra were produced at Hanscom Air Force Base and are online at <https://users.physics.unc.edu/~gcsloan/library/standards>.

⁶ Appendix C1 describes the LRS characterizations in more detail.

Table 2
Bright Red Giants Used as Infrared Standards

Target	IRAS PSC	Spectral Type	SWS	Used for New Correction	PSC F_{12}^a (Jy)	LRS F_{12} (Jy)	Hanscom F_{12} (Jy)	LRS/Hanscom
β Gem	07422+2808	K0 III	no	yes	85.9	85.8	74.7	1.149
α Boo	14133+1925	K1.5 III	yes	yes	547.0	522.6	458.4	1.140
α TrA	16433–6856	K2 III	no	no	99.3	110.1	90.0	1.223
α Hya	09251–0826	K3 II–III	no	no	108.7	91.9	89.5	1.027
ϵ Car	08214–5920	K3 III	no	no	169.7	169.2	158.8	1.065
β UMi	14508+7421	K4 III	yes	yes	110.6	110.9	98.1	1.130
α Tau	04330+1624	K5 III	yes	yes	482.6	448.2	407.8	1.099
γ Dra	17554+5129	K5 III	yes	yes	107.0	118.2	96.4	1.226
β And	01069+3521	M0 III	yes	no	197.7	193.2	171.8	1.125
μ UMa	10193+4145	M0 III	yes	no	69.6	49.9	64.8	0.770
α Cet	02596+0353	M1.5 III	yes	yes	161.9	191.0	146.0	1.308
β Peg	23013+2748	M2.5 II–III	yes	no	267.1	254.3	254.1	1.001
γ Cru	12283–5650	M3.5 III	yes	yes	596.8	624.4	591.8	1.055

Note.

^a Color corrected by dividing by 1.45.

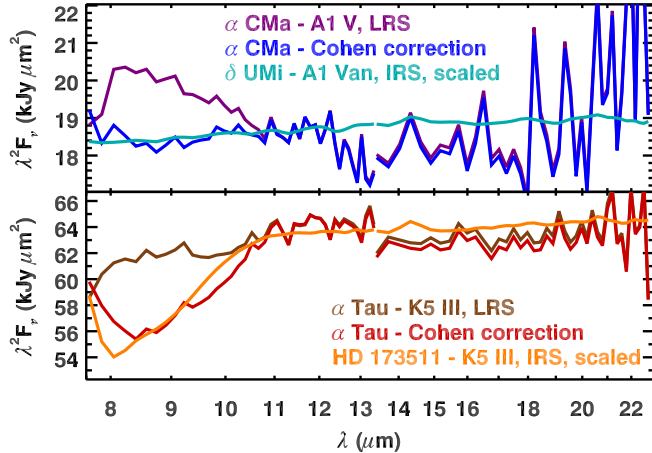


Figure 4. A comparison of LRS spectra of the A dwarf α CMa and the K giant α Tau with spectra from the Spitzer/IRS of standard stars with similar spectral types. The LRS spectra are plotted with and without the spectral correction derived by M. Cohen et al. (1992a; i.e., the Cohen correction). In the Rayleigh–Jeans units used, stellar spectra with no absorption bands should be almost horizontal, with a gentle rise from the blue end, as δ UMi illustrates. The spectra from the IRS are down-sampled to the resolution of the LRS and scaled.

The other is α Tau (Aldebaran), one of two K giants used as primary standards in the infrared in the past (along with Arcturus, or α Boo). Figure 4 compares their LRS spectra to spectra of standard stars with similar spectral types obtained with the Infrared Spectrograph (IRS) on the Spitzer Space Telescope (G. C. Sloan et al. 2015). The uncorrected LRS spectrum of α CMa shows an SiO emission artifact at $8\,\mu\text{m}$ when it should follow a Rayleigh–Jeans tail and be roughly horizontal. The uncorrected LRS spectrum of α Tau is missing the strong SiO absorption band apparent in the IRS spectrum of HD 173511.

M. Cohen et al. (1992a) derived a spectral correction to remove the SiO artifact from the LRS Atlas. Their correction, hereafter the Cohen correction, is based on ratios of red giants to A dwarfs, most notably α Tau to α CMa and α Boo to

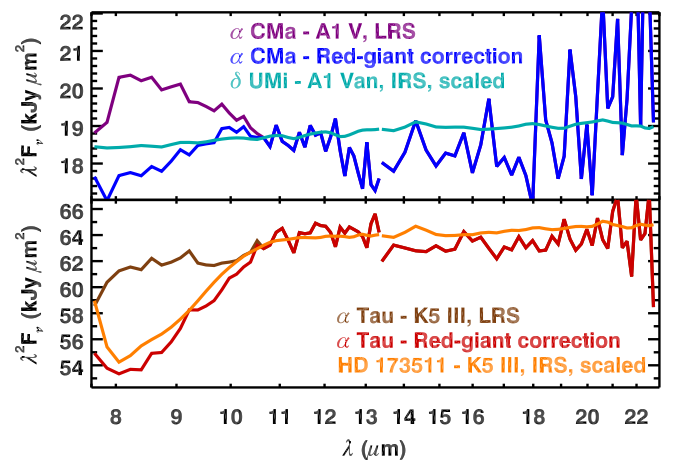


Figure 5. Testing the spectral correction derived from red giants. While the recovered shape of the SiO absorption band at $\sim 8\text{--}11\,\mu\text{m}$ has improved in α Tau, the shape of the spectrum of α CMa has grown worse in the same wavelength range, especially at the blue end of the spectrum.

α Lyr. The published correction used a wavelength grid with a different break between the blue and red LRS segments than ours, and we have determined values for the six missing wavelength elements at the red end of the blue segment ($12.81\text{--}13.34\,\mu\text{m}$) by linear interpolation. Applying the Cohen correction greatly improves the LRS spectra, but the profile of the SiO band in α Tau still does not match the profile in HD 173511. This comparison of a spectrum from the LRS on IRAS to the IRS on Spitzer requires that the IRS data be down-sampled to match the much lower resolution of the LRS; otherwise, the difference in resolution would result in different band shapes.

We have improved the Cohen correction by comparing LRS spectra of bright red giants and warmer stars used as infrared standards. Appendix B describes our methodology in detail. This section focuses on the results and explains the reasoning. We first attempted to use just the best red giants (starting with Table 2). Figure 5 presents the results of that effort. While the

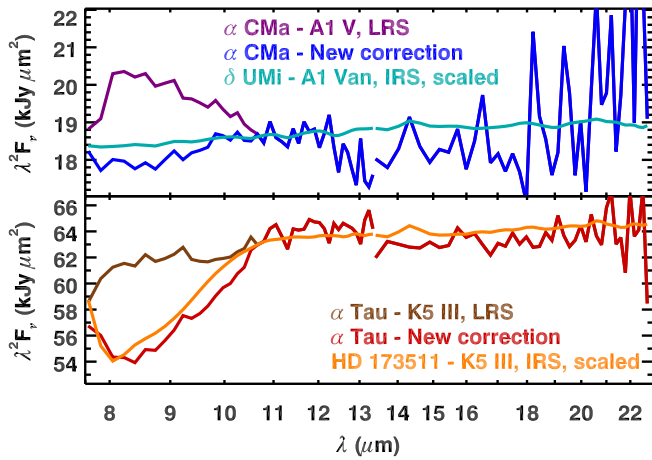


Figure 6. The results of applying the new spectral correction, which is derived from both red giants and warmer stars. The new correction reproduces the SiO band in a late K giant well, and it reduces the degradation of the A dwarf at the blue end.

red-giant correction improves the overall shape of the SiO absorption band at $\sim 8\text{--}10\ \mu\text{m}$ in α Tau, some differences in shape remain compared to HD 173511. More notably, the spectrum of α CMA, which should be flat in Rayleigh–Jeans units, drops from $\sim 10\ \mu\text{m}$ to the blue end of the spectrum.

The ambiguous results from the spectral correction based on red giants led us to also consider using warmer stars, such as the A dwarfs α CMA and α Lyr. Appendix B provides the details. Combining the corrections from the red giants and warm stars results in a new correction, which we have adopted in place of the older Cohen correction. Figure 6 presents the results. Compared to the red-giant correction, the new correction better reproduces the shape of the SiO band in α Tau. While it does not completely eliminate the drop between 7.7 and $10\ \mu\text{m}$ in α CMA, it does reduce it below $9\ \mu\text{m}$.

The differences in the overall strength of the SiO absorption band in the corrected spectrum of α Tau compared to HD 173511 could easily be astrophysical in nature, as the spread in overall band strengths in giants of the same spectral class is well documented (A. Heras et al. 2002; C. W. Engelke et al. 2006; G. C. Sloan et al. 2015). However, the *shape* of the SiO band is more uniform from one source to the next (G. C. Sloan et al. 2015, see their Figure 13). Thus, the apparent structure in the band from 8.5 to $10.6\ \mu\text{m}$ in the LRS data probably indicates the limitations of the LRS spectra. The deviations in α CMA compared to δ UMi tell a similar story. The difference at $\sim 8\text{--}9\ \mu\text{m}$ is $\sim 2\%$, which reflects the overall spectral fidelity of the LRS database. The deviations past $12\ \mu\text{m}$ are likely due to noise in the data, because a blue star is rapidly growing fainter to longer wavelengths.

The new spectral correction has been applied to the entire extended LRS atlas. The individual spectral data files are provided with flux densities with and without the correction. (Appendix D provides more details on the spectral data products.)

Using the two sets of standards, the red giants and the warm stars, to generate a spectral correction should give the same answer. The fact that they do not points to a limitation of $\sim 2\%\text{--}3\%$ in the spectral fidelity of the LRS. Thus, the LRS data are useful for general spectral analysis but perhaps less suited to detailed spectral modeling.

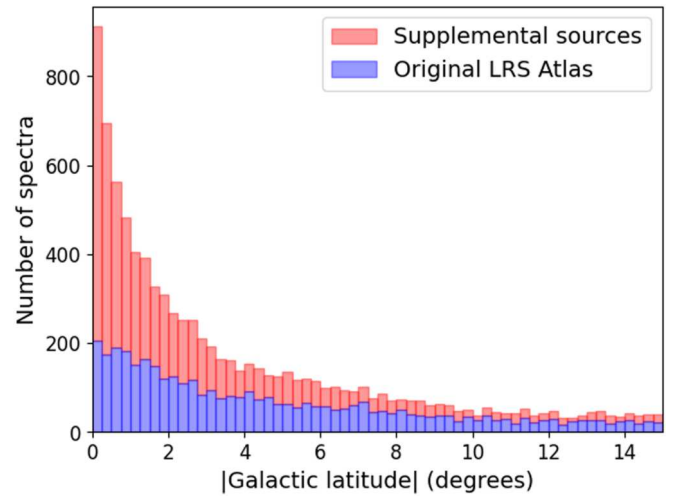


Figure 7. A layered histogram showing the distribution of sources in the original LRS Atlas and the supplemental sources as a function of Galactic latitude close to the Galactic plane. The bin closest to the plane has 205 original sources and 707 supplemental and extra sources, for a total of 912 sources.

4. Completeness

Figure 7 illustrates how the original LRS Atlas is missing sources close to the Galactic plane. The histogram is presented in layers, so that the first bin includes a total of 912 sources, 205 in the original LRS Atlas and 707 from the supplemental and extra sources. The ratio of supplemental and extra sources to original sources in the full catalog is 1.07 ($5813/5425$), while the corresponding ratio of sources in that innermost bin is 3.45 . Within 2° of the Galactic plane, the ratio is still 2.05 . Those differences should give some idea of how the strict selection criteria of the original LRS Atlas selected heavily against sources in the crowded fields near the Galactic plane.

The decreasing completeness of the LRS Atlas toward the Galactic plane is a result of the large beam size of IRAS, which leads to significant uncertainties in the positions of sources. Formally, the IRAS resolution element at $12\ \mu\text{m}$ would be $5''.3$ across. For point sources, the actual radial uncertainty has a Gaussian $\sigma = 8''.4$ (in the cross-scan direction; C. A. Beichman et al. 1988). To determine better positions for the sample, we searched SIMBAD⁸ for positions and cross-checked those by searching for sources within $15''$ in the AKARI/Infrared Camera Point Source Catalog (IRC PSC; D. Ishihara et al. 2010) at 9 and $18\ \mu\text{m}$ (AKARI Team 2020).

AKARI has counterparts to 10,599 of the 11,238 sources in the extended LRS Atlas (94%). Of the 639 missing sources, 125 are in the original LRS Atlas of 5425 sources (i.e., 2.3% from the LRS Atlas are missing). The remaining 564 missing sources represent 9.7% of the 5813 additional sources. The two telescopes have similar sizes and resolutions. The AKARI primary was $0.67\ \text{m}$ in diameter, giving a resolution element at $12\ \mu\text{m}$ of $4''.6$ compared to $5''.3$ for IRAS.

Table 3 presents the results of the AKARI search by focusing on what is missing, broken down by the object type as defined by the LRS characterizations. Table 4 does the same for the spectral classifications defined by K. Volk & M. Cohen (1989a; also referred to as the VC89 classes). These tables provide brief definitions of the classifications, while

⁸ <http://simbad.u-strasbg.fr/simbad/>

Table 3
Missing Sources in AKARI by LRS Characterization

LRS Char.	Description	Missing	Out of	Percentage
0n	Unusual	6	363	1.7
1n	Blue, star	26	2238	1.2
2n	Blue, silicate emission	42	1730	2.4
3n	Blue, silicate absorption	13	230	5.7
4n	C-rich dust	9	538	1.7
5n	Red, featureless	6	63	9.5
6n	Red, silicate emission	1	78	1.3
7n	Red, silicate absorption	7	67	10.4
8n	PAHs	8	69	11.6
9n	PAHs, no lines	7	49	14.3

Table 4
Missing Sources in AKARI by VC89 Class

VC89 Class	Description	Missing	Out of	Percentage
S	Dust-free star	9	1635	0.6
F	Star + some dust	37	1944	1.9
E	Silicate emission	114	3617	3.2
A	Silicate absorption	25	319	7.8
C	C-rich dust	8	715	1.1
P	PAHs	55	315	17.5
H	Red continuum	185	638	29.0
U	Unusual	67	661	10.1
L	Lines	0	31	0.0
I	Incomplete	139	1363	10.2

Appendix C2 describes them and compares the two systems more thoroughly.

AKARI recovers the vast majority of the stellar sources, and the difference between the original atlas and the full extended atlas is small. Comparing LRS characterizations 1n, 2n, and 4n to the similar VC89 classes, S, F, E, and C, gives similar rates of missing sources, 1.7% and 2.1%, respectively.

The percentage of missing sources rises for the redder sources. For LRS characterizations 5n–9n, AKARI missed 8.9% of the sources, compared to 20.3% of VC89 classes A, P, H, and L. The latter percentage includes sources in the original LRS Atlas, plus the supplemental sources. The redder sources tend to be associated with star-forming regions, which have complex backgrounds, are generally close to the Galactic plane and therefore in crowded fields, and can be extended. For the supplemental sources, all of those issues are more pronounced. Both IRAS and AKARI would be challenged to identify targets with these characteristics, so the higher percentage of missing targets is expected, for both the red spectra in general and the supplemental red spectra in particular. Plus, we were matching to the AKARI point-source catalog, which selects against the more extended targets that can appear in the LRS database.

The red spectra in the LRS database should be treated with some caution. Because the LRS data were obtained as IRAS scanned across the sky with no slit, it is possible that the wavelength calibration may not be as accurate for some extended sources. Furthermore, the scanning nature of the spectrometer leads to greater positional uncertainties for the extended sources. For sources in complex fields in the Galactic plane, more recent surveys should be consulted to better determine what structures were likely to contribute to the LRS

spectra, such as the MSX survey (S. D. Price et al. 2001) and the GLIMPSE survey (R. A. Benjamin et al. 2003; E. Churchwell et al. 2009).⁹

5. Summary

The new version of the extended LRS atlas contains 11,238 mid-infrared spectra obtained by IRAS in 1983 covering nearly the entire sky. That total comprises all of the 5425 spectra in the original LRS Atlas; 5796 from the additional data published by K. Volk & M. Cohen (1989a), K. Volk et al. (1991), and S. Kwok et al. (1997), and 17 extra unpublished spectra previously available on data servers. The spectra have a spectral resolving power between 20 and 60.

This version of the LRS atlas has corrected the spectra to remove the SiO artifact centered at 8 μ m present in earlier available databases. However, the derivation of that correction with different populations of stars reveals systematic differences that expose some limitations in the spectra. We estimate that the spectral fidelity is $\sim 2\%$ – 3% . Separate photometric analysis reveals a $\sim 13\%$ difference between the calibration of the LRS on IRAS and the PSC for bright stars, and that difference increases by another $\sim 10\%$ for fainter stars in the LRS Atlas.

The sources added after the release of the original LRS Atlas greatly improve the sampling close to the Galactic plane. The vast majority of the spectra in the database arise from point sources, as indicated by the recovery of 94% of them in the AKARI/IRC PSC. These point sources are predominantly dust-free stars or stars with optically thin dust shells. Roughly 11% of the sample are red spectra, which may arise from extended sources and complex fields and may have less reliable wavelength calibrations.

The extended LRS atlas remains the closest we have to a complete spectral survey of the mid-infrared sky. The total number of sources, 11,238, compares favorably to such fundamental surveys as the Yale Bright Star Catalog, which includes 9110 stars and defines the bright optical sky. In the same way, the extended LRS atlas defines the bright mid-infrared sky. It is now back in the public domain!

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Facilities: IRAS, ISO (SWS), Spitzer (IRS), AKARI (IRC).

Appendix A Defining the Sample

The sample of spectra from the LRS published here is based on the source list for the extended LRS catalog published by S. Kwok et al. (1997) and the spectra in the Calgary database.

⁹ Galactic Legacy Infrared Midplane Survey Extraordinaire.

Table 5
Rejected or Renamed Sources from S. Kwok et al. (1997)

Target	Action	Reason
02187–0302	Rejected	Redundant; typo for 02168–0312
05580+1633	Rejected	Redundant; typo for 05583+1633
07136+2851	Renamed	Now 07316+2851
16262–2619A	Renamed	Now 16262–2619
19200+2101	Rejected	Redundant with 19199+2100
Egg Nebula	Renamed	Now 21003+3629M

Not all targets from those two sources made it to the final catalog.

S. Kwok et al. (1997) published a list of 11,224 spectra, which included the 5425 spectra from the original catalog (the LRS Atlas; F. M. Olnon et al. 1986) and 5799 supplemental spectra. The latter group included 386 spectra from K. Volk & M. Cohen (1989a), 456 from K. Volk et al. (1991), and 4957 new sources. For the discussion below, we will refer to these three groups of spectra as the VC89, V91, and K97 sources. We kept all but three of these spectra, omitting one from V91 and two from K97. In addition, we renamed three of the sources. Table 5 summarizes the changes.

The rejected source from V91 is IRAS 19200+2101. SIMBAD considers this source and two others (IRAS 19199+2100 and IRAS 19201+2101) to be a blend of two objects and gives all three the same coordinates. SIMBAD reports that the actual objects are OH 55.1 +3.1, an OH/IR star, and UCAC4 556-089440, a star about which little is known. The LRS spectrum of IRAS 19201+2101 shows silicate absorption at 10 μ m, which is consistent with the OH/IR star. The spectra of IRAS 19199+2100 and IRAS 19200+2101 in the Calgary database are identical, and both are red, making them a poor match to a star. The SIMBAD association to UCAC4 556-089440 appears to be incorrect. We kept IRAS 19199+2100 and dropped IRAS 19200+2101, but it was arbitrary which spectrum should be excluded.

Two K97 sources were also rejected. IRAS 02187–0302 is not in the PSC and has a spectrum identical to the VC89 source IRAS 02168–0312 (better known as Mira). IRAS 05580+1633 is not in the PSC, has no LRS data associated with it in the database, and appears to be a typo for the K97 source IRAS 05583+1633.

Three other supplemental sources were renamed. IRAS 07136+2851 is a typo for IRAS 07316+2851 in the original LRS Atlas. Antares (α Sco) was identified as IRAS 16262–2619A, but in the list by VC89 (and in the PSC) it is IRAS 16262–2619. Finally, the Egg Nebula (AFGL 2688) is one of the three sources recovered from the strip in Cygnus with no counterparts in the PSC. We assigned these three sources PSC-like names based on their 1950 coordinates and appended the suffix “M” for “missing.” Thus, AFGL 2688 becomes IRAS 21003+3628M.

Table 6 lists the 22 extra unpublished sources in the Calgary database. We retained 17 of those, and of those 17, we renamed three because the Calgary server did not provide PSC-based names. V3811 Sgr appears in the PSC as IRAS 18206–2157. NML Cyg and V407 Cyg are in the strip of Cygnus missing from the PSC. As with AFGL 2688, they do not have PSC counterparts, and we generated names appended with “M.”

Table 6
Extra Sources

Target	Action	Reason	Class
01555+5239	Kept	...	U
05437+2420	Kept	...	E
05588+1633	Rejected	Redundant, typo for 05583+1633	...
06230+1748	Rejected	Redundant with 06230+1749	...
09553–6150	Kept	...	F
16445–4459	Kept	...	I
16458–4512	Kept	...	H
16492–4349	Kept	...	A
17006–4215	Kept	...	H
17118–3909	Kept	...	H
17143–3700	Kept	...	A
17230–3459	Kept	...	L
17478–2649	Kept	...	A
V3811 Sgr	Renamed	Now 18206–2157	H
18329–0629	Kept	...	U
18358–0647	Kept	...	A
18408–0353	Kept	...	H
NML Cyg	Renamed	Now 20445+3955M	F
20445+3956	Rejected	Redundant with 20445+3955M	...
V407 Cyg	Renamed	Now 21004+4534M	E
A05336+6846	Rejected	Spectrum is just zeros	...
R Leo	Rejected	Redundant with 09448+1139	...

Five of the extra spectra in the Calgary database were excluded. The target identified as IRAS A05336+6846 has a spectrum with just zeros for its signal, and no source close to this position appears in the PSC. The remaining four rejects duplicate other spectra. R Leo appears twice, once with its variable-star designation and once as the VC89 source IRAS 09448+1139; we kept the latter. Similarly, we have IRAS 06230+1748 and the K97 source IRAS 06230+1749. Both spectra are identical, and we retained the latter designation. IRAS 05588+1633 was rejected because it appears to be another typo for IRAS 05583+1633 (a K97 source) and has no data associated with it. IRAS 20445+3956 was rejected because it is not in the PSC, and it has a spectrum identical to another extra source, NML Cyg, which we have already renamed to IRAS 20445+3955M.

For the surviving 17 extra sources, we classified them using the system developed by K. Volk & M. Cohen (1989a) and described in Appendix C2. Two of the spectra had classifications on the Calgary server, and those remain unchanged: “F” for IRAS 09553–6150, and “I” for IRAS 16445–4459. A third source, IRAS 17230–3459, had the undefined classification “d” on the Calgary server, and we have classified it as “L” due to the emission lines in its spectrum.

Thus, out of 11,224 spectra from K97, we have omitted three, leaving 11,221. Of the 22 extra spectra, we have kept 17, for a total of 11,238 spectra.

Appendix B Determining the Spectral Correction

For the red giants, the sample used for the spectral correction started with the list of 13 bright red giants used as infrared standard stars in Table 2. Nine of those stars appear in Table 1 from C. W. Engelke et al. (2006), which they describe as their “best secondary standards,” after the two primary standards, the A dwarfs α CMa and α Lyr. Of those nine red giants, we already rejected μ UMa (see Section 2.3). For the

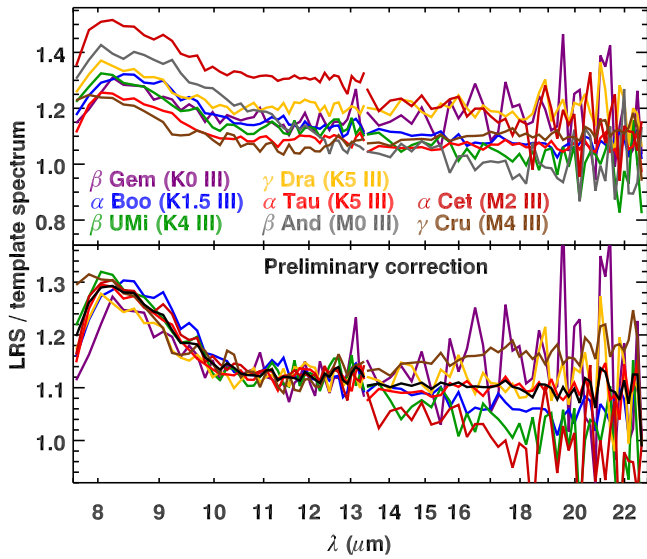


Figure 8. Assembling the spectral correction for the red giants. Top: the ratios of the LRS spectrum divided by the template spectrum for the same star. Bottom: the same ratios, after normalization to the flux-weighted mean at 10.6–13.4 μm , along with the preliminary spectral correction derived from the individual ratios (in black).

remaining eight, we use as a spectral template the Hanscom spectrum, which for seven of the eight is based on the spectrum from the SWS and shifted to be consistent with the photometry. The exception is β Gem, for which C. W. Engelke et al. (2006) substituted spectra of stars with similar spectral types, using the SWS spectrum of θ Cen (K0–IIIb) below 9 μm and the spectrum from ISOCAM on ISO of δ Dra (G9 III) past 9 μm . For cooler K giants, the variation in strength of the SiO band within a spectral class could lead to errors in the strength of the band, but a K0 giant shows little SiO absorption, so any errors should be small.

The top panel of Figure 8 plots the ratio of the uncorrected LRS spectrum to its template for the eight red giants. Seven show a similar shape, with the SiO band apparent (with a flipped sign) from the blue end to $\sim 10.6 \mu\text{m}$, and a flat structure from there to the long-wavelength end of the blue segment at 13.4 μm . The exception is β And (in gray), which falls steadily past 10.6 μm . We have removed it from the sample. The flux-weighted mean ratio from 10.6 to 13.4 μm of the seven surviving spectra is 1.123 ± 0.025 (uncertainty in the mean), which compares favorably to the ratio of 1.129 ± 0.026 found in Section 2.3 with a larger sample of red giants and a smaller wavelength range. Much of the uncertainty in the sample considered here is driven by α Cet (ratio 1.306). The large star-to-star variations reinforce the conclusion that the absolute photometric calibration of the LRS is not reliable and further support the decision to not correct the LRS database photometrically.

The bottom panel of Figure 8 shows the spectral ratios after scaling them to the same ratio between 10.6 and 13.4 μm (1.123). All seven ratios show similar structure through the SiO band. The mean spectral ratio with each star weighted by its PSC flux density gives the preliminary spectral correction based on the red giants.

As Figure 5 shows, the spectral correction based solely on red giants forces the spectrum of α CMa downward at the blue end (below $\sim 9.5 \mu\text{m}$) even as it improves the shape of the SiO band in α Tau compared to the Cohen correction. Therefore, we also generated a correction using five bright stars with higher effective

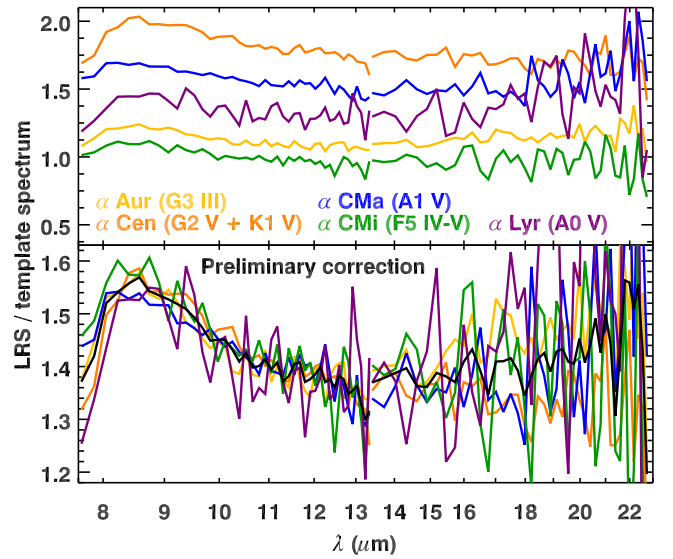


Figure 9. Assembling the spectral correction for the warm stars. As in Figure 8, the top and bottom panels show the ratios of LRS to spectral template before and after normalization at 10.6–13.4 μm . The plotting range in the top panel is much wider than in Figure 8 to accommodate the greater spread in the ratios of spectrum to template.

Table 7
Bright Warm Stars Used as Infrared Standards

Target	IRAS PSC	Spectral Type	PSC F_{12}^a (Jy)
α Lyr	18352+3844	A0 V	28.7
α CMa	06429–1639	A1 V	98.7
α CMi	07366+0520	F5 IV–V	54.5
α Cen	14359–6037	G2 V + K1 V	153.2
α Aur	05130+4556	G3 III	162.8

Note.

^a Color corrected by dividing by 1.45.

temperatures than the red giants. Table 7 lists the sample. The A dwarfs α CMa and α Lyr are the current and former all-sky standards, respectively, and C. W. Engelke et al. (2006) include α Cen and α Aur in their lists of secondary standards (their Tables 2 and 3, respectively). For all four, we use Hanscom spectra as templates. For the two A dwarfs, these templates are based on models. For α Cen, the template is based on the SWS data, scaled to the photometry calibrated to align with the MSX calibration. For α Aur, the Hanscom spectrum is a template based on the star’s spectral type and scaled to the photometry. We excluded one warm star listed by C. W. Engelke et al. (2006), β Dra, because it is too faint. We added a fifth star, α CMi, because it is bright and easily characterized. For its template, we used the BOSZ model generated as described in Section 2.2.

Figure 9 shows the construction of the preliminary spectral correction for the warm stars listed in Table 7. The top panel shows the spectral ratios before they have been normalized. The most obvious difference between the warm stars and the red giants is the much wider range of spectral ratios. The bottom panel shows that despite that wide range, the ratios are reasonably consistent in the wavelength range covered by the SiO artifact.

The mean correction from 10.6 to 13.4 μm is based on a flux-weighted average of 1.375 with an uncertainty in the

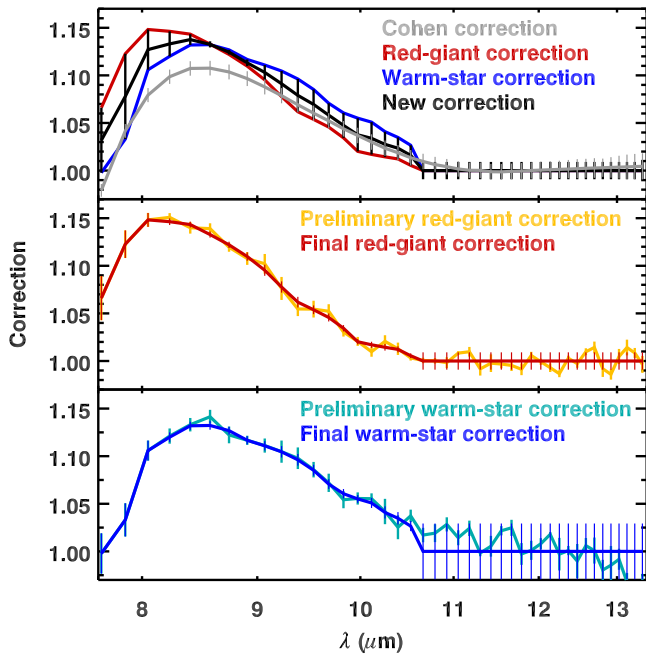


Figure 10. Combining the spectral corrections from the red giants and warm stars. Top: the new correction is the average of the corrections for the red giants and warm stars determined in the bottom two panels, and the Cohen correction is included for comparison. Middle and bottom: determining the final corrections for the red giants and warm stars, respectively. The orange and light-blue curves give the preliminary corrections, and the dark-red and dark-blue curves give the final corrections. The error bars in the Cohen correction are as reported by M. Cohen et al. (1992a); all other error bars are the uncertainty in the mean.

mean of 0.140. The spread in the ratios of LRS to template in the warm stars is significantly larger than in the red giants and reinforces the case for not attempting a photometric correction to the LRS database.

Beyond $13.4\ \mu\text{m}$, i.e., in the red spectral segment, the spectral ratios vary significantly from star to star in both the red giants and the warm stars, even after normalization at $10.6\text{--}13.4\ \mu\text{m}$. A uniform spectral correction applied to all data would do nothing to improve the situation, leading us to set the correction to 1.0 for all of the red spectral segment.

Figure 10 shows how the new spectral correction has been determined from the preliminary corrections for the red giants and warm stars. For both samples, the preliminary corrections in the bottom panels of Figures 8 and 9 are normalized to 1.0 at $10.6\text{--}13.4\ \mu\text{m}$ by dividing by the mean ratios, 1.123 and 1.375, respectively. The spectra are then smoothed with a 3-pixel boxcar to reduce the noise. For the red giants, the spectra are flat from 10.6 to $13.4\ \mu\text{m}$ and normalized to 1.0 there, making any spectral structure in that range likely just noise. Therefore, at $10.6\text{--}13.4\ \mu\text{m}$, we have set the correction to 1.0 and the uncertainty in the correction to the standard deviation of the corrections at each wavelength, 0.0091. The correction from the warm stars receives the same treatment, except that the uncertainty is 0.0293. These uncertainties in the correction are extended to the red end of the red segment.

The top panel of Figure 10 shows the new correction, which is the mean of the corrections from the two samples. The uncertainties redward of $10.6\ \mu\text{m}$ are taken directly from the red-giant correction. The corrections from the red giants and warm stars for the SiO artifact differ systematically, with the warm-star correction slightly weaker and shifted to longer

wavelengths. It also drops back to ~ 1.0 at the blue end of the spectrum. These differences are a concern, because all of the spectra in the LRS database should show identical artifacts and require the same spectral correction. No obvious cause for the differences between the warm stars and red giants stands out. Generally, the red giants are brighter than the warm stars, but within the red giants, Figure 8 does not reveal any significant differences between the three brightest red giants, γ Cru, α Boo, and α Tau, all with $F_{12} \sim 500\text{--}600\ \text{Jy}$, and the rest of the sample. Similarly, the three faintest red giants, β Gem, β UMi, and γ Dra, with $F_{12} \sim 80\text{--}110\ \text{Jy}$, do not stand out as a group. Two have slightly weaker artifacts to correct for, but otherwise their shape resembles the rest of the red giants.

Figure 10 includes the Cohen correction for comparison. It resembles the warm-star correction somewhat more than the red-giant correction, although it is weaker, with a peak correction $\sim 10\%$, versus 13% for the warm stars and 14% in the combined new correction.

Appendix C Infrared Spectral Classifications

S. Kwok et al. (1997) provided infrared spectral classifications based on the VC89 scheme for the entire sample using simple one-letter designations. The 5425 spectra in the original LRS Atlas also have a two-digit LRS characterization that provides more information (F. M. Olmon et al. 1986). We have retained both of these classifications, and this appendix describes and compares them. It also compares the VC89 classifications to schemes developed for the spectrometers aboard ISO. Tables 8 and 9 outline the LRS characterizations and the VC89 system, and Table 9 gives approximate equivalences between the two systems.

C.1. LRS Characterizations

The LRS characterization scheme was partially automated, starting by fitting a power law to the spectra from 14 to $22\ \mu\text{m}$. If the spectral index β was less than -1 , where $F_\lambda \sim \lambda^\beta$, then the spectrum was assigned to $1n$ through $4n$, depending on the dominant spectral features. Otherwise, the spectrum was assigned to $5n\text{--}9n$. Noisy spectra or spectra that did not fit the other categories were assigned to $0n$. Table 8 simplifies the descriptions of the subclasses (n) given by Table 1 from F. M. Olmon et al. (1986), which should be consulted for further details.

Blue spectra dominated the LRS Atlas, with the three most populous classes being the featureless spectra ($1n$), the silicate emission spectra ($2n$), and the carbon-rich spectra ($4n$). Combined, these spectra account for 83% of the original LRS Atlas. Dust-free stars generally had LRS characterizations of 18, since the Rayleigh–Jeans tail of a star should fall as $\beta = -4$ (and $n = -2\beta$), with noise spreading the range of characterizations to $17\text{--}19$. Sources with low-contrast dust emission (typically from alumina) fell into the range $14\text{--}16$ (G. C. Sloan & S. D. Price 1995). Sources with low-contrast oxygen-rich or carbon-rich dust emission can wind up with characterizations anywhere in the low 20s, 30s, or 40s because of noise in their spectra. This confusion can be seen in tables with LRS characterizations of independently verified dust chemistries, such as oxygen-rich dust in S stars (I. R. Little-Marenin & S. J. Little 1988, their Table 1), dust in oxygen-rich AGB stars (G. C. Sloan & S. D. Price 1998, their Table 4), and dust in carbon stars (G. C. Sloan et al. 1998, their Table 2).

Table 8
LRS Characterizations

LRS Char.	Description	N	Fraction of Total (%)	Second Digit
$0n$	Unusual or low-S/N spectra	363	6.7	$n = 0-5$, depending on the spectral shape
$1n$	Blue featureless spectra	2238	41.3	$n = -2\beta$, where $F_\lambda \sim \lambda^\beta$
$2n$	Silicate emission at $10\ \mu\text{m}$	1730	31.9	n increases with feature strength
$3n$	Silicate absorption at $10\ \mu\text{m}$	230	4.2	n as $2n$
$4n$	SiC dust emission at $11.3\ \mu\text{m}$	538	9.9	n as $2n$
$5n$	Red featureless spectra	63	1.2	$n = 2\beta$, where $F_\lambda \sim \lambda^\beta$
$6n$	As $2n$, but with a red continuum	78	1.4	n increases with feature strength
$7n$	As $3n$, but with a red continuum	67	1.2	n as $6n$
$8n$	PAHs and emission lines	69	1.3	n based on the strongest line
$9n$	Emission lines and no PAHs	49	0.9	n as $8n$

Table 9
Spectral Classes from K. Volk & M. Cohen (1989a) (VC89)

Spectral Class	Description	N	Fraction of Total (%)	Analogous LRS Characterizations ^a
S	Dust-free stellar continuum	1635	14.5	16–19 , 01
F	Featureless nonstellar blue continuum	1944	17.3	13–16 , 01
E	Silicate emission at $10\ \mu\text{m}$	3617	32.2	2n , 13–16, 42–43, 69, 01
A	Silicate absorption at $10\ \mu\text{m}$	319	2.8	3n
C	SiC dust emission at $11.3\ \mu\text{m}$	715	6.4	4n , 14–17
P	PAH emission features	315	2.8	80 , 32–35, 81
H	Red continuum	638	5.7	91 , 80–81, 05, 7n , 5n
L	Emission lines	31	0.3	94–95
U	Unusual spectrum	661	5.9	12–15, 50, 21–23, 01
I	Incomplete or noisy spectrum	1363	12.1	01, 05, 1n , 50

Note.

^a The predominant LRS characterizations are in bold.

These inconsistencies in relating the LRS characterizations directly to classes of objects (dust-free stars, oxygen-rich stars with optically thin dust shells, etc.) arise from the limited S/N in the sample. This problem grows with the fainter samples that dominate the sources added in the supplemental catalogs, making it unwise to apply the LRS characterizations to the full sample of 11,238 spectra. Each spectrum does have a classification in the system introduced by K. Volk & M. Cohen (1989a), making it the better system for navigating the full LRS database.

C.2. VC89 Classifications

The “S” class is for stellar spectra with no dust, while the “F” class includes other featureless blue spectra that are falling less steeply with wavelength than a Rayleigh–Jeans tail, most likely because of low-contrast dust emission. Effectively, these two classes split the $1n$ LRS characterizations. Of the 1171 class S spectra in the original LRS Atlas, 751 (64%) are 17 or 18, with another 161 characterized as 01 and about 100 each as 16 and 19. Of the 1014 class F spectra with LRS characterizations, 759 (75%) are in the range 14–16, 90 are 01, and 54 are class 13.

Most optically thin oxygen-rich dust shells are classified as “E” to denote emission from silicate and related dust. Of the 2082 in the LRS Atlas, 1659 (80%) have LRS characterizations of $2n$. Another 250 (12%) are in the range 12–17, with most in 13–16. The confusion of low-contrast carbon-rich and oxygen-rich dust emission has placed 55 in the range 41–45 (mostly 41–43).

Interestingly, 45 of the class E sources have LRS characterizations of 69, indicating strong silicate emission and a red continuum. These sources are primarily oxygen-rich post-AGB objects. Another 37 are in the $0n$ range, most of them 02.

The optically thick oxygen-rich dust shells with silicate absorption features at $10\ \mu\text{m}$ and/or $18\ \mu\text{m}$ are classified as “A” and are better behaved than the class E sources. Of the 125 in the LRS Atlas, 115 (92%) are in the $3n$ sequence.

The carbon-rich “C” class includes 565 sources in the LRS Atlas, with most of these (437, or 77%) on the $4n$ sequence. Of the remainder, 87 (15%) are characterized as $1n$ (most of them 14–17), 21 are characterized as $0n$, and 16 are scattered among 21–24 and 31–32.

The remaining VC89 classes are less populated in the LRS Atlas and tend to be scattered across more characterizations, making them more difficult to map onto the LRS characterizations. The PAH emission sources (“P”) are a good example. Of the 121 in the LRS Atlas, 27 have an LRS characterization of 80 (PAHs and no emission lines), with 9 others on the $8n$ sequence, 47 on the $3n$ sequence, 15 on the $1n$ sequence, and 10 on the $7n$ sequence. The “U” class catches many unusual spectra. Many have flat continua or cooler blackbody spectra that peak in the LRS wavelength range, which implies a temperature of 200–300 K. For a spectrum to be classified as “H” (for H II regions), it must continue rising to the long-wavelength end of the spectrum. Classes “L” and “I” include spectra dominated by emission lines and incomplete spectra, respectively.

While the LRS characterizations and the VC89 classes are most relevant to the new extended LRS atlas, other classification systems are also available. A Bayesian classification scheme led to what has become known as the Autoclasses (P. Cheeseman et al. 1989), which placed the 5425 spectra in the original atlas in 77 self-defined classes. I. R. Little-Marenin & S. J. Little (1988, 1990) classified over 400 optically thin oxygen-rich circumstellar dust shells in the original atlas by the shape of the spectral emission profile instead of the strength of the feature that drove the LRS characterizations. G. C. Sloan & S. D. Price (1995, 1998) generalized the shape-based approach by defining a silicate dust sequence and applied it to over 600 LRS spectra. That number is still just a fraction of the total of oxygen-rich dust sources in the extended LRS atlas.

C.3. Comparison to ISO-based Classification Systems

Comparing the VC89 system to the classification scheme developed by K. E. Kraemer et al. (2002) for the ISO/SWS reveals both its strengths and its weaknesses. The primary weakness of the VC89 system compared to the SWS classification results from the limitations of the LRS data, with their lower spectral resolution, reduced wavelength coverage, and lower angular resolution. The full-scan spectra from the SWS cover 2.4–45 μm with a spectral resolving power of several hundred, compared to 7.67–23.73 μm and 20–60 for the LRS. These improvements allowed a more thorough scheme for the SWS, which classified spectra in five groups from blue to red, with dust-free stellar spectra in group 1, stars with increasing amounts of circumstellar dust in groups 2 and 3, and increasingly red spectra from more evolved objects, nebulae, and young stellar objects in groups 4 and 5. Group 6 was reserved for spectra with no continuum, and group 7 was reserved for spectra with major flaws in the data. The SWS classifications added descriptors to the group numbers such as “N” for naked (i.e., dust-free) stars, “SE” for silicate and related oxygen-rich dust emission, “SA” for silicate dust absorption, “CE” for carbon-rich dust emission, and “U” for PAH emission (previously known as the UIR, or unidentified infrared emission features). This system leads to many more classifications than just the 10 classes in the VC89 system.

K. E. Kraemer et al. (2002) found that the classifications of the stellar spectra in the VC89 system aligned closely with the SWS classifications. We repeated their analysis and found a total of 776 spectra of sources in common between the SWS sample (as defined by G. C. Sloan et al. 2003) after excluding offset targets and group 7 spectra. Of the 111 matched class S spectra, 90% are classified as dust-free stars (1.N, with various subclasses), and most of the remainder are stars with low-contrast alumina dust emission (2.SEa). Of the 172 matched class E spectra, 65% have SWS spectra classified as optically thin oxygen-rich dust emission (2.SE), 18% have optically thick silicate dust in emission or partial self-absorption (3.SE and 3.SB), and another 7% have silicate emission superimposed on a red continuum (4.SE). Of the 67 matched class C spectra, all but two of the SWS spectra are classified as carbon-rich (49 in group 2; 16 in group 3). The matched class F spectra align well with low-contrast dust emission, with 55% of the spectra classified as 2.SEa. Folding in the 1.N and remaining 2.SE sources increases the percentage to 67%, but the remainder are scattered, with 13% in group 3 and 3% in group 4. To summarize, the spectra from the SWS validate the majority of the VC89 classifications for the relatively blue spectra in classes S, F, E, and C.

The redder VC89 classes, however, show substantially more scatter. The best behaved group is class P. Of the 45 matched spectra, 71% have a “U” or “u” in their SWS classifications, with the lowercase “u” indicating the presence of PAHs in a spectrum dominated by something else. Another 20% of the class P spectra are matched to SWS spectra with silicate absorption in their spectra, because both can produce similar shapes in the limited wavelength range available to the LRS. Of the 162 matched class H spectra, nearly all are in groups 4 or 5, indicating that the SWS spectra confirms their red continua. However, 31% are associated with SWS class 5.UE, indicating that PAH emission features rival the atomic emission lines in strength. It follows that users searching for PAH emission should not limit themselves to the P class. The SWS classifications for the 25 matched L spectra reveal that 92% of them have continuum shapes and spectral features suggesting that they are planetary nebulae.

The remaining classes, U and I, are more difficult to generalize, which should be expected for unusual and incomplete spectra. The 76 matched class U spectra, interestingly, include 25 reddened carbon-rich spectra (with classifications 4.CR, 4.CT, 4.CN, and 4.C/SC). Otherwise, the class U spectra are scattered from group 1 to group 6. The 11 matched class I spectra are predominately in group 5, probably because the sources are extended and in complex backgrounds where a complete spectrum could not be extracted.

T. M. Hodge et al. (2004) also compared the VC89 classifications with the scheme developed by K. E. Kraemer et al. (2002). They classified spectra observed by the PHT-S spectrometer on ISO that cover the wavelength ranges 2.5–4.9 μm and 5.8–11.6 μm . The PHT-S sample included 237 sources with spectra from the LRS, and they verified that most of the VC89 classifications of blue spectra agreed well between the LRS and PHT-S. However, the differences in wavelength coverage and sensitivity between the two sets of spectra can occasionally lead to significantly different classifications. From the current and previous comparisons, the lesson emerges that the VC89 classifications should be used as a guide and not relied on to be precise, more so for the redder classes than the bluer ones.

Appendix D Accessing the Extended Atlas

The individual spectra in the extended LRS atlas will be available from the Infrared Science Archive (IRSA) at IPAC.¹⁰ The data are also available from Harvard Dataverse at doi:10.7910/DVN/3028UI. Additional data files are also available, including the LRS wavelength grid with the resolution at each wavelength element and the four spectral corrections on that grid described in this paper (the Cohen correction, the corrections from the red giants and warm stars, and the final correction from the combination of those two).¹¹

Each spectral data file has five columns: wavelength (μm), flux density (Jy), uncertainty in flux density (Jy), a segment identifier, and the raw flux density (Jy). The flux density column is after the application of the spectral correction, and the raw flux density is before. The uncertainties are all zeros because they are not provided in the original data, but they are included because some software will expect that column in the

¹⁰ <http://irsa.caltech.edu>

¹¹ All data files are also available at <https://users.physics.unc.edu/~gcsloan/library/lrsatlas>.

Table 10
The Catalog of Sources in the Extended LRS Atlas

Target IRAS PSC	R.A. (deg, J2000)	Decl. (deg, J2000)	Position Reference ^a	Source	LRS Char.	VC89 Class	IRAS F_{ν} ^b (Jy)	IRAS F_{ν} ^b (Jy)	AKARI F_{ν} ^b (Jy)	AKARI F_{ν} ^b (Jy)
00001+4826	0.684258	48.714115	2020yCat.1350....0G	original	21	E	48.870	24.100	33.78	14.15
00007+5524	0.839422	55.681120	2020yCat.1350....0G	original	22	E	97.600	46.920	124.00	58.51
00012+6626	0.965171	66.712183	2020yCat.1350....0G	original	18	S	12.690	3.220	17.22	3.97
00017+3949	1.083645	40.109952	2020yCat.1350....0G	original	16	F	17.740	6.850	21.39	8.92
00019+4150	1.126582	42.119910	2020yCat.1350....0G	kwok97	−1	F	18.680	6.905	21.05	7.44
00019−1047	1.125493	−10.509524	2007A&A...474..653V	original	1	S	12.730	3.363	17.07	3.95
00020+4316	1.151698	43.551313	2020yCat.1350....0G	original	18	S	10.420	3.385	13.19	3.87
00036+6117	1.571383	61.565894	2003yCat.2246....0C	kwok97	−1	F	7.225	4.174	11.14	5.65
00036+6947	1.559355	70.067281	2020yCat.1350....0G	original	44	C	36.570	9.936	31.18	8.43
00039+2648	1.621968	27.090110	2020yCat.1350....0G	original	16	F	16.920	6.250	18.80	6.74

Notes.

^a The bibcode references are to (in order of mention) Gaia EDR3 (released in 2020; Gaia Collaboration et al. 2021), Hipparcos (F. van Leeuwen 2007), and the Two Micron All Sky Survey (released in 2003; M. F. Skrutskie et al. 2006).

^b The photometry is not color corrected.

(This table is available in its entirety in machine-readable form in the [online article](#).)

data files. The segment identifier is 1 for the blue segment (7.67–13.34 μm) and 2 for the red segment (13.41–22.73 μm). Each file has a header with the ancillary data in Table 10.

For each spectrum, Table 10 provides the IRAS PSC name (reconstructed with “M” for the three missing sources), the position from SIMBAD (in degrees), and a reference for that position provided as a bibcode as referenced by SIMBAD and the Astrophysics Data System.¹² The source column has a value of “original” for the original LRS Atlas, “vc89” for K. Volk & M. Cohen (1989a; V89), “volk91” for K. Volk et al. (1991; V91), and “kwok97” for S. Kwok et al. (1997; K97). The LRS characterizations have a value of −1 for sources not in the original LRS Atlas, and the VC89 classifications are as given by S. Kwok et al. (1997) or Table 6. Table 10 also has the uncorrected flux densities at 12 and 25 μm from the IRAS PSC and at 9 and 18 μm from the AKARI/IRC PSC, all in Jy. Missing fluxes have a value of −1 Jy.

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References

- AKARI Team 2020, AKARI/IRC Point Source Catalogue, IPAC, doi:10.26131/IRSA181
- Beichman, C. A., Neugebauer, G., Habing, H. J., et al. 1988, *Infrared Astronomical Satellite (IRAS) Catalogs and Atlases. Volume 1: Explanatory Supplement* (2nd ed.; Washington, DC: NASA)
- Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, *PASP*, **115**, 953
- Bohlin, R. C., Mészáros, S., Fleming, S. W., et al. 2017, *AJ*, **153**, 234
- Cheeseman, P., Stutz, J., Self, M., et al. 1989, *Automatic Classification of Spectra from the Infrared Astronomical Satellite NASA-RP 1217*, NASA
- Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, *PASP*, **121**, 213
- Cohen, M., Walker, R. G., & Witteborn, F. C. 1992a, *AJ*, **104**, 2030
- Cohen, M., Witteborn, F. C., Carbon, D. F., et al. 1992b, *AJ*, **104**, 2045
- Engelke, C. W. 1992, *AJ*, **104**, 1248
- Engelke, C. W., Price, S. D., & Kraemer, K. E. 2006, *AJ*, **132**, 1445
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, *A&A*, **649**, A1
- Glaccum, W. 1995, in *ASP Conf. Ser. 73, Airborne Astronomy Symp. on the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M. R. Haas, J. A. Davidson, & E. F. Erickson (San Francisco, CA: ASP), 39
- Grasdalen, G. L., & Gaustad, J. E. 1971, *AJ*, **76**, 231
- Hacking, P., Neugebauer, G., Emerson, J., et al. 1985, *PASP*, **97**, 616
- Heras, A., Shipman, R. F., Price, S. D., et al. 2002, *A&A*, **394**, 539
- Hodge, T. M., Kraemer, K. E., Price, S. D., & Walker, H. J. 2004, *ApJS*, **151**, 299
- Ishihara, D., Onaka, T., Kataza, H., et al. 2010, *A&A*, **514**, 1
- Kraemer, K. E., Sloan, G. C., Price, S. D., & Walker, H. J. 2002, *ApJS*, **140**, 389
- Kwok, S., Volk, K., & Bidelman, W. P. 1997, *ApJS*, **112**, 557
- Leech, K., Kester, D., Shipman, R., et al. 2003, in *The ISO Handbook, Vol. V–SWS: The Short Wavelength Spectrometer, v2.0.1*, ed. T. G. Mueller, J. A. D. L. Blommaert, & P. Garcia-Lario (Paris: European Space Agency),
- Little-Marenin, I. R., & Little, S. J. 1988, *ApJ*, **333**, 305
- Little-Marenin, I. R., & Little, S. J. 1990, *AJ*, **99**, 1173
- Little-Marenin, I. R., & Price, S. D. 1986, in *NASA Ames Research Center Summer School on Interstellar Processes: Abstracts of Contributed Papers* (Washington, DC: NASA), 137
- Mészáros, S., Bohlin, R., Allende Prieto, C., et al. 2024, *A&A*, **688**, 197
- Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, *ApJL*, **278**, L1
- Neugebauer, G., Habing, H. J., van Duinen, R., et al. 2019, *IRAS Point Source Catalog v2.1 (PSC)*, IPAC, doi:10.26131/IRSA4
- Neugebauer, G., & Leighton, R. B. 1969, *Two-micron Sky Survey. A Preliminary Catalogue* (Washington, DC: NASA),
- Olson, F. M., Raimond, E., Neugebauer, G., et al. 1986, *A&AS*, **65**, 607
- Onaka, T., de Jong, T., & Willems, F. J. 1989, *A&A*, **218**, 169
- Price, S. D., Egan, M. P., Carey, S. J., et al. 2001, *AJ*, **121**, 2819
- Price, S. D., Paxson, C., Engelke, C., & Murdock, T. L. 2004, *AJ*, **128**, 889
- Price, S. D., Sloan, G. C., & Kraemer, K. E. 2002, *ApJL*, **565**, L55
- Price, S. D., & Walker, R. G. 1976, *The AFGL Four Color Infrared Sky Survey: Catalog of Observations at 4.2, 11.0, 19.8, and 27.4 Micrometer AFGL-TR-76-0208*, Hanscom AFB
- Rieke, G. H., Engelke, C., Su, K., & Casagrande, L. 2023, *AJ*, **165**, 99
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, **131**, 1163
- Sloan, G. C., Herter, T. L., Charmandaris, V., et al. 2015, *AJ*, **149**, 11
- Sloan, G. C., Kraemer, K. E., Price, S. D., & Shipman, R. F. 2003, *ApJS*, **147**, 379
- Sloan, G. C., Little-Marenin, I. R., & Price, S. D. 1998, *AJ*, **115**, 809
- Sloan, G. C., & Price, S. D. 1995, *ApJ*, **451**, 758
- Sloan, G. C., & Price, S. D. 1998, *ApJS*, **119**, 141
- Takigawa, A., Tachibana, S., Nagahara, H., et al. 2015, *ApJS*, **218**, 2
- van Leeuwen, F. 2007, *A&A*, **474**, 653
- Volk, K., & Cohen, M. 1989a, *AJ*, **98**, 931, (VC89)
- Volk, K., & Cohen, M. 1989b, *AJ*, **98**, 1918
- Volk, K., Kwok, S., Stencel, R. E., & Brugel, E. 1991, *ApJS*, **77**, 607

¹² <http://ui.adsabs.harvard.edu>