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0.8–13.5 MICRON SPECTROSCOPY OF IRAS 07077+1536: A DUSTY CARBON STAR

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ABSTRACT

Contemporaneous near-infrared (0.8–2.5 μm) and infrared (3–14 μm) spectroscopy is presented of the previously uncharacterized *IRAS* source 07077+1536. The data show it to be a carbon star embedded in a circumstellar dust envelope. The near-infrared spectrum displays molecular absorption features of C_2, CN, and CO, while the 11 μm emission feature from SiC is present in the thermal infrared. The spectral energy distribution of IRAS 07077+1536 is similar to the so-called extreme carbon stars in that it consists primarily of a reddened stellar photosphere and thermal dust emission. However, the extinction is much less and the dust significantly warmer (~900 K vs. ~300 K) than in extreme carbon stars such as AFGL 3068. IRAS 07077+1536 is also unusually bright shortward of 0.5 μm, an aspect that could be due to variability but may indicate the presence of a binary companion or a foreground star.

Key words: dust, extinction — infrared radiation — stars: carbon — stars: individual (IRAS 07077+1536)

1. INTRODUCTION

The *IRAS* survey was particularly successful at finding dust enshrouded carbon stars in its 12 and 25 μm bands (e.g., Skinner & Griffin 1989). These objects are very faint at optical wavelengths and were uncovered by their large, excess emission in the thermal infrared. In fact, embedded carbon stars detected by *IRAS* account for about one-quarter of the known carbon stars (Guglielmo et al. 1993). At shorter wavelengths, the Two Micron All Sky Survey (hereafter 2MASS; Skrutskie et al. 1997) is, and will be, a source for finding previously undetected carbon stars (e.g., Liebert et al. 2000; Nikolaev & Weinberg 2000). In the course of a program investigating sources from 2MASS, one particular object, 2MASSI J0710398+153115, came to our attention through its peculiar near-infrared colors. A positional search of these coordinates revealed a coincidence with the *IRAS* source 07077+1536 (*IRAS* uses epoch B1950.0 coordinate designations, while 2MASS employs epoch J2000.0), but a literature search found no investigations of this object.

In 2002 January, we had the opportunity to obtain both near-infrared and thermal infrared spectroscopy of IRAS 07077+1536. These data show it to be a dust-enshrouded, carbon-rich giant, manifesting the reddening and dust emission of the "extreme carbon stars" (Volk, Xiong, & Kwok 2000), but to a lesser degree. However, optical surveys indicate that IRAS 07077+1536 is also surprisingly bright in the blue. The entire spectral energy distribution (SED) in addition to some of the near-infrared absorption features characteristic of a carbon-rich giant are discussed below.

2. OBSERVATIONS

The near-infrared observations of IRAS 07077+1536 were obtained on the night of 2002 January 28 (UT) using the Shane 3 m reflector of Lick Observatory. The instrument employed was The Aerospace Corporation's Near-Infrared Imaging Spectrograph (NIRIS; Rudy, Puetter, & Mazuk 1999), a long-slit spectrograph that uses two channels to provide nearly continuous coverage between 0.8 and 2.5 μm. A beam splitter that switches from reflection to transmission at 1.38 μm separates the channels. The focal plane arrays, which employ HgCdTe as the detector material, are two-quadrant HAWAII devices that each provide 1024 channels in the spectral dimension and 300 in the spatial direction. The spatial resolution is $0\overset{''}{.}4$ pixel^{-1}. The spectral resolution is constant over each channel and is determined by the width of the entrance slit. It was 16 Å for the blue channel and 37 Å for the red for the 3″ slit width employed for our observations of IRAS 07077+1536. The acquisition and reduction of data using NIRIS are described by Rudy et al. (2002). The comparison star observed together with IRAS 07077+1536 and used to remove the instrumental response and to reduce the effects of atmospheric absorption was HR 2007, a G4 V–type star with $V = 5.97$ (Hoffleit & Jaschek 1982). The intrinsic continuum of HR 2007 was assumed to match that of a model from Kurucz (1994) with solar metallicity, $T_{\rm eff} = 5500$ K, and log (surface gravity) = 4.25, values appropriate to this spectral type and luminosity class. Small adjustments were made to the width and strength of the stronger stellar absorption features (e.g., the calcium infrared triplet and the Paschen lines) in the model to match the actual observations. An absolute flux scale was determined by normalizing to the *K* magnitude for HR 2007. The *K* magnitude (4.45) was calculated from the *V* magnitude and the $V-K$ color for a G4 dwarf tabulated by Koornneef (1983). The resulting spectrum of IRAS 07077+1536 is shown in Figure 1.

Infrared spectrophotometric data from 3 to 13.5 μm were acquired on the night of 2002 January 15 (UT) with the 3 m reflector of the Infrared Telescope Facility (IRTF). The

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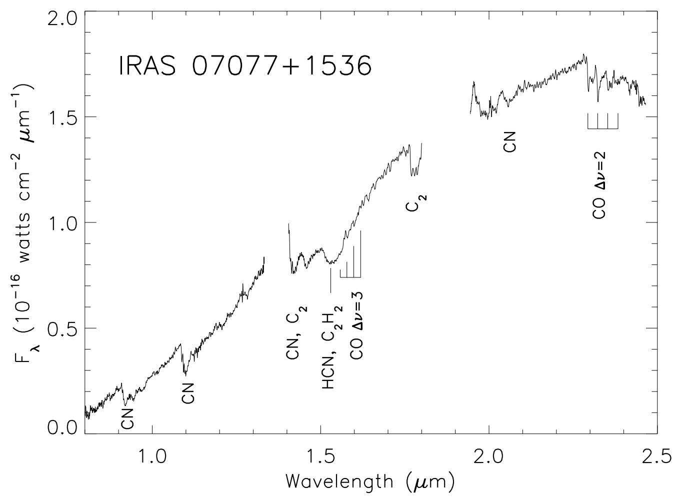

FIG. 1.—Near-infrared spectrophotometry of IRAS 07077+1536. Molecular absorption bands are labeled. The features of CN and C_2 are signatures of a carbon-rich (C > O) star. Band head locations for the first and second overtones of CO are shown. The broad absorption feature at 1.53 μm is probably due to HCN or C_2H_2 or both (see text).

instrument used was the Aerospace Corporation's Broadband Array Spectrograph System (BASS), which is described in detail by Hackwell et al. (1990). Briefly, BASS uses two curved prisms and two 116 element Si:As blocked impurity band linear arrays (operated at liquid helium temperatures) to cover the 3–6.5 and 5.6–14 μm regions. Data are obtained simultaneously at all wavelengths using the same 3$''$.2 diameter aperture. Chopping and nodding were 20$''$ east to west at 7.1 Hz. The calibration star was Sirius (α CMa), whose spectrum at our wavelengths and resolutions is equivalent to an 11,200 K blackbody scaled to magnitude -1.41 at 10 μm. For zero magnitude, we adopted the value of 1.26×10^{-16} W cm^{-2} μm^{-1} at 10.0 μm. These observations of IRAS 07077+1536 are presented in Figure 2.

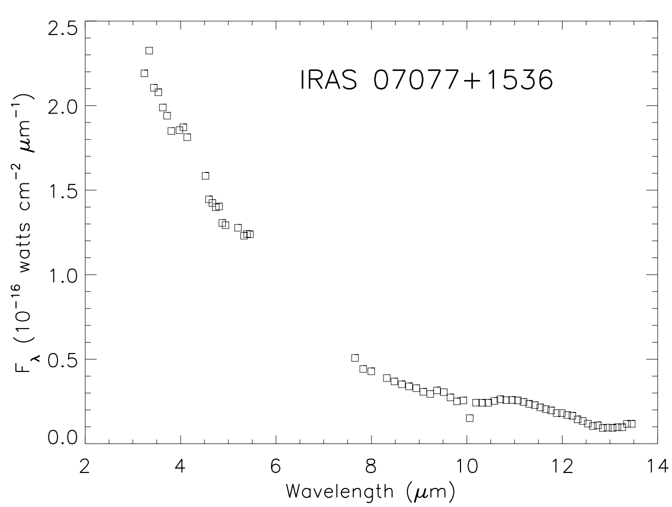

FIG. 2.—The 3–13.5 μm spectroscopy of IRAS 07077+1536. The SiC emission feature is the broad rise around 11 μm—it is shown in greater detail in Fig. 3. Blanks in the spectral coverage around 4.3 μm are because of telluric absorption by CO_2; those between 5.5 and 7.5 μm are caused by H_2O.

3. RESULTS

For clarity of presentation, this section is divided into two subsections, one dealing with the spectral features manifested by IRAS 07077+1536, and a second discussing the overall energy distribution of its continuum. The former shows that IRAS 07077+1536 is carbon-rich; the latter shows the degree to which the photospheric emission is absorbed and reradiated by dust but also points out the unusual optical brightness.

3.1. *Spectral Features*

Identifications for the absorption features in the 0.8–2.5 μm portion of the spectrum of IRAS 07077+1536 are given in Figure 1. The Ballik-Ramsay bands of C_2 are present, along with several features of CN (Goebel et al. 1983). The existence of the CN and C_2 features clearly indicate that IRAS 07077+1536 is carbon-rich—if the object were oxygen-rich (O > C), all available carbon would be incorporated into CO (Gilman 1969; Salpeter 1974), and the other molecules of carbon would not be present. Also present is a broad absorption at around 1.53 μm. This feature was attributed to HCN or C_2H_2, or a combination of both, by Goebel et al. (1981) and is discussed in detail by Joyce (1998). Other references that are useful in comparing IRAS 07077+1536 with carbon stars in the near-infrared include Lancon & Wood (2000) and Skinner & Griffin (1989).

The first overtone of carbon monoxide, formed from the $\Delta\nu = 2$ vibrational transitions, is seen beginning at 2.29 μm. The 2–0 and 3–1 band heads at 2.2929 and 2.3220 μm (air wavelengths) are distinct. Weaker but also present are two band heads from the second overtone: the 4–1 at 1.5775 μm and the 5–2 at 1.5982 μm. The 3–0 band head at 1.5577 μm is obscured by the 1.53 μm absorption feature mentioned above. Higher bands in the first overtone are also present but are not as well-defined as those at shorter wavelengths. This is due partially to the lower signal-to-noise of the data at longer wavelengths where both the rising thermal background and increased telluric absorption affect the quality of the measurements. Unfortunately, this includes the 2–0 band of ^{13}CO (which is blended with the 4–2 band of ^{12}CO), which might have allowed a measurement of the important ^{12}C/^{13}C ratio (Wallerstein & Knapp 1998).

Present in the thermal infrared is another feature that is characteristic of carbon-rich giants. It is the solid-state feature of SiC (Treffers & Cohen 1974), and it is shown in detail in Figure 3. The feature arises from dust grains that form in the outer atmosphere of the star and is distinct from the silicate (SiO_2) feature that might be present if the star were oxygen-rich.

The size, shape, and central wavelength of the SiC feature have been studied by numerous investigators using both ground-based and space-based instruments (e.g., Cohen 1984; Little-Marinen 1986; Goebel, Cheesman, & Gerbault 1995; Speck, Barlow, & Skinner 1997). In a study of 176 sources with good *IRAS* LRS spectra, Little-Marinen (1986) found a mean wavelength of 11.15 $\pm$ 0.10 μm for the SiC feature. The central wavelength in IRAS 07077+1536 (11.0 μm) is only slightly smaller than this value but is at the extreme short-wavelength end of the distribution found by Speck et al. (1997). Of the 32 sources they observed, only the SiC emission of R Lep had a similar shape and wavelength of peak emission.

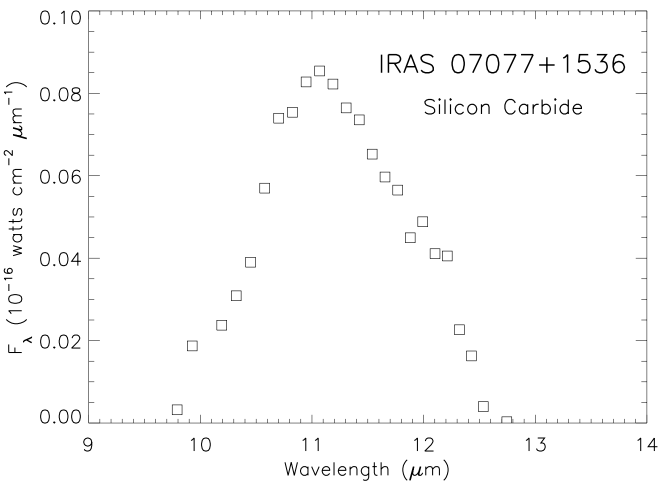

FIG. 3.—SiC emission of IRAS 07077+1536. The underlying continuum has been subtracted to show the feature in greater relief. The feature is produced by hot dust that forms in the outer atmospheres of some carbon-rich giants.

Mutschke et al. (1999) have derived the optical constants of various types of SiC, both crystalline and amorphous, using transmission spectroscopy of powders produced by various methods. They also calculate the theoretical absorption coefficients from dielectric constants of SiC polytypes using different axial distributions. The SiC emission feature in IRAS 07077+1536 is similar in both central wavelength and full width half-maximum to the predicted spectra of crystalline SiC particles with ellipsoidal shapes.

3.2. *Spectral Energy Distribution*

Figure 4 shows our spectrophotometry together with the visible, near-infrared (2MASS), and thermal infrared (*IRAS*) photometry. The photometry is summarized in Table 1. Errors for the 2MASS and *IRAS* data are those quoted in the catalogs. The *IRAS* catalog fluxes have been corrected for the color of the spectrum according to the prescription of the *IRAS* Explanatory Supplement (Beichman et al. 1988). The corrections amounted to reductions in the catalog flux values by factors of 1.24 and 1.33 at 12 and 25 μm, respectively. The B and R magnitudes were estimated from the values reported for the nearby field stars by the 2MASS software that are drawn from the compilation of the Naval Research Observatory (Monet et al. 1998) and from the Digital Sky Survey.

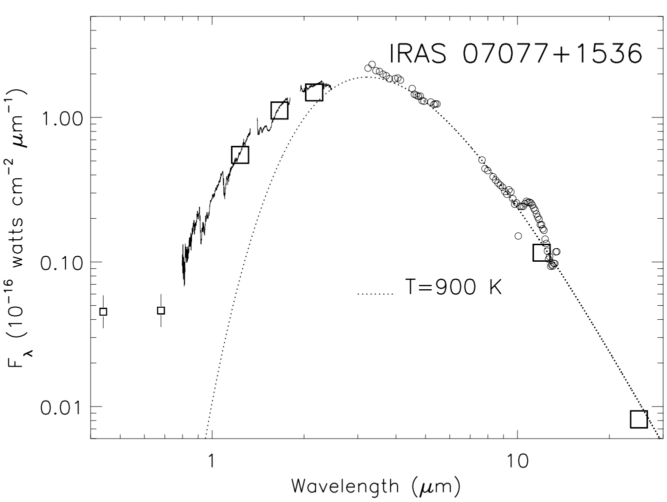

FIG. 4.—SED of IRAS 07077+1536. The figure shows both our near-infrared (0.8–2.5 μm, *solid line*) and thermal infrared (3–13.5 μm, *small open circles*) spectrophotometry. The broadband photometry that is encoded with large squares includes J, H, and K_s from the 2MASS program and 12 and 25 μm from the *IRAS* survey. The B and R from the Digital Sky Survey are encoded with small squares such that the error bars (0.3 mag) can be shown. With the exception of the excess emission in the blue, the SED of IRAS 07077+1536 matches that of a heavily reddened stellar photosphere and a warm blackbody.

TABLE 1
PHOTOMETRY OF IRAS 07077+1536

Filter	Wavelength (μm)	Magnitude or Flux
B	0.44	15.0 ± 0.3
R	0.68	14.0 ± 0.2
J	1.235	9.39 ± 0.031
H	1.662	7.50 ± 0.015
K_s	2.159	6.15 ± 0.013
12	12	5.56 ± 0.35[a]
25	25	1.70 ± 0.32[a]

[a] *IRAS* Catalog flux corrected for continuum shape matching a 900 K blackbody in janskys.

There are three important aspects of the SED that are apparent in Figure 4: (1) the reddened stellar continuum that forms the near-infrared portion of the SED, (2) the warm thermal component that accounts for the emission beyond 3 μm, and (3) the excess emission blueward of 0.5 μm.

With regard to reddening, the photosphere is clearly significantly extinguished. The likely color temperature for the underlying photosphere in the near-infrared is ~2000–2500 K (Wallerstein & Knapp 1998) with a peak in the flux between 1.1 and 1.4 μm, in contrast to what is observed. However, to place IRAS 07077+1536 within the framework of previously observed carbon stars, it is important to quantify the reddening, specifically the value of A_V, since this is what is quoted in previous studies. Because there are no pairs of emission lines with known intrinsic ratios to serve as reddening metrics, the reddening must be estimated from the observed shape of the stellar photosphere. Fortunately, this requires only a small extrapolation of our spectrum (from 0.8 to 0.55 μm). Before this can be accomplished, however, the flux contribution from the warm dust must be removed. We do this by simply extrapolating the single temperature (900 K) blackbody that is fitted at longer wavelengths.

An additional complication in estimating the extinction is present because it does not follow a standard interstellar reddening curve. The purely carbon dust grains are not the standard mix observed in the interstellar medium, and because the dust surrounds the star, scattering by the grains can return some light to the line of sight as well remove it. Therefore, to estimate the visual extinction from the observed shape of the near-infrared continuum, we employed both the " standard " infrared interstellar reddening curve of Draine (1991) and a purely absorptive model based on amorphous carbon and SiC. For the latter model, we took the absorption cross sections for 0.05 μm spherical particles from Ivezic & Elitzur (1995).

The value for the visible extinction derived from the reddening curve of Draine is $A_V = 7.0 \pm 0.6$, while the value for the absorptive carbon grains is $A_V = 6.2 \pm 0.6$. While significant, the visible extinction of IRAS 07077+1536 is small by comparison with the five carbon stars of Volk et al. (2000) where all values for A_V exceeded 80. Volk et al. (2000) classified these five as extreme carbon stars. These objects are similar to perhaps the best known obscured carbon star, IRC +10216 (see Kelly & Latter 1995 for a near-infrared spectrum), but the archetype for the extreme carbon stars is AFGL 3068 (Lebofsky & Rieke 1977; Jones et al. 1978). For this class of star, the photosphere is almost totally obscured and the near-infrared continuum is produced primarily by the dust emission. IRAS 07077+1536 lacks this severe local extinction and is more similar to the two *IRAS* sources investigated by Skinner & Griffin (1989). The observed near-infrared colors for IRAS 17446−7802 ($J-H = 1.8$, $H-K = 1.6$) and IRAS 07454−7112 ($J-H = 1.6$, $H-K = 1.2$) are similar to those of IRAS 07077+1536 ($J-H = 1.89$, $H-K = 1.35$), and the near-infrared flux is similarly produced by the combination of a reddened stellar photosphere and emission from warm dust.

From the estimation of the reddening and the relative contribution to the SED from dust and knowledge of the intrinsic luminosity for objects like IRAS 07077+1536, it is possible to calculate its distance. Our values for the reddening and the amount of dust emission indicate an apparent *K*-band magnitude of ∼5.9 for the unreddened stellar photosphere. Wallerstein & Knapp (1998) have derived distances for a number of types of carbon stars from *Hipparcos* parallaxes. They find mean values of $M_K = -6.5$ for the Lb and SRb variables and −7.6 for the Miras and the SRa variables. Claussen et al. (1987) suggested values up to −8.5 for objects at the tip of the asymptotic giant branch, while Wallerstein & Knapp (1998) reference values up to −9.2 in the LMC and −9.6 in the clusters NGC 1751 and 1978. This results in a wide range for the distance modulus, 12.4–15.5, and in the corresponding distance, 3.1–12.7 kpc. Even allowing for the low galactic latitude of 4°.9, the range of out of the plane distances of IRAS 07077+1536 (260–1100 pc) exceeds the scale height of ∼180–200 pc of the SRb's and Miras (Claussen et al. 1987; Groenewegen et al. 1992; Kerschbaum & Hron 1992). Thus, there is a good chance that IRAS 07077+1536 belongs to the halo, similar to the dusty carbon giants discussed by Liebert et al. (2000).

The other principal contributor to the bulk luminosity of IRAS 07077+1536, and the second feature of the SED to which we wish to call attention, is the component due to warm dust (see Fig. 4). The portion of the spectrum from 3 through 25 μm matches a 900 K blackbody remarkably well. This 900 K value for the temperature is an additional factor that distinguishes IRAS 07077+1536 from the more extreme AFGL 3068–type objects. The color temperature that best matched the spectrum of AFGL 3068 was 325 K (Jones et al. 1978), while the values of the sources observed by Volk et al. (2000) were between 200 and 300 K. These very low temperatures are due to the large optical depths of the dust shells. Because they can have optical depths exceeding unity at 11 μm, the emission from hotter dust that is closer to the star is absorbed by the cooler, outer dust and reradiated at the latter's characteristic temperature. In contrast, the much smaller degree to which the stellar photosphere of IRAS 07077+1536 is reddened (the visual extinction estimated above indicates a *K*-band extinction of only about a factor of 2) indicates that its dust shell is optically thin for wavelengths beyond 3 μm.

The final feature of the SED that we wish to highlight is the optical brightness, specifically the *B* magnitude, which represents a clear departure from the reddened stellar continuum (see Fig. 4). Extreme carbon stars discovered by *IRAS* typically tend to be very faint optically (Skinner & Griffin 1989). Volk et al. (2000) found a comparatively bright ($V = 16.5$) optical flux for the extreme carbon star IRAS 00210+6221 and suggested that it might be transforming into a proto–planetary nebula. Since all of the extreme carbon stars are objects near the tip of the asymptotic giant branch and undergoing profuse mass loss, this is a real possibility. However, this is not the case for IRAS 07077+1536, where we directly observe the stellar continuum, and it is still that of a late-type giant.

Because we detect the stellar emission from IRAS 07077+1536, we can also rule out a preferred line of sight as the cause of the optical brightness. If the shell did not entirely surround the star, it might be possible to view the stellar photosphere along a relatively unobscured direction while still receiving the infrared flux radiated by the shell. However, because the infrared emission from the star itself is reddened, the optical flux will be as well.

Possibilities that could reconcile the optical brightness with the large reddening are (1) that the object is variable, (2) that there is a binary companion that accounts for the visible light, or (3) that there is a visible star with very nearly the same line of sight. IRAS 07077+1536 is certainly variable, as are all the objects of this type. Although the mass loss, and thus the extinction, probably changes, it is not clear whether the blue flux could have reached the level observed.

Similarly, we can say little observationally about the existence of a binary companion except that there is no obvious presence of it in our spectrophotometry. For a main-sequence star, this would indicate that it should have a spectral type around late F or earlier, otherwise it would contribute measurably to the flux around 0.8 μm. From the distance estimates given above and the assumption of no reddening, the star would have to be earlier than A5 for it to be a gravitationally linked to IRAS 07077+1536. Even the small amount of interstellar reddening that is likely to be present in this direction (Hakkila et al. 1997) will drive the spectral type to even earlier values.

Finally, to check the possibility of second object along the same line of sight of IRAS 07077+1536, the three 2MASS images (*J*, *H*, and *K*) were overlain on the blue and red plates from the Digital Sky Survey. In matching the locations of four nearby stars, it appeared that the infrared location of IRAS 07077+1536 was displaced approximately 1″ west of the putative optical counterpart. If real, this separation could be explained by the presence of either a gravitationally unrelated object in the same direction or a widely separated companion. Optical spectroscopy should be able to either establish or rule out a binary association by providing a spectral type, and thus a distance, for the visible counterpart.

4. SUMMARY

Infrared spectroscopy combined with *IRAS* and 2MASS photometry has been presented for the *IRAS* source 07077+1536. It shows a reddened stellar continuum at wavelengths shorter than ~2.5 μm, and a thermal dust component at a single temperature (900 K) beyond. IRAS 07077+1536 is interesting because it is a carbon star intermediate in its properties between those of visual carbon stars and the extreme carbon stars that populate the tip of the asymptotic giant branch. In addition, IRAS 07077+1536 displays a SiC emission feature that peaks shortward of the nominal 11.3 μm value and is unusually bright at optical wavelengths. Optical spectroscopy is encouraged to explain the brightness below 0.5 μm as are radio CO measurements to determine the outflow velocity and estimate the mass-loss rate.

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REFERENCES

Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., & Chester, T. J. 1988, IRAS Catalogs and Atlases: Explanatory Supplement (NASA RP-1190) (Washington: GPO), 1

Claussen, M. J., Kleinmann, S. G., Joyce, R. R., & Jura, M. 1987, ApJS, 65, 385

Cohen, M. 1984, MNRAS, 206, 137

Draine, B. T. 1990, in Infrared Spectroscopy in Astronomy, ed. B. H. Kaldeich (ESA SP-290) (Noordwijk: ESA), 93

Gilman, R. C. 1969, ApJ, 155, L185

Goebel, J. H., Bregman, J. D., Cooper, D. M., Witteborn, F. C., & Taylor, B. J. 1983, ApJ, 270, 190

Goebel, J. H., Bregman, J. D., Witteborn, F. C., & Taylor, B. J. 1981, ApJ, 246, 455

Goebel, J. H., Cheesman, P., & Gerbault, F. 1995, ApJ, 449, 246

Groenewegen, M. A. T., de Jong, T., van der Bliek, N. S., Slijkhuis, S., & Willens, F. J. 1992, A&A, 253, 150

Guglielmo, F., Epchtein, N., Le Bertre, T., Fouqué, P., Hron, J., Kerschbaum, F., & Lepine, J. R. D. 1993, A&AS, 99, 31

Hackwell, J. A., et al. 1990, Proc. SPIE, 1235, 171

Hakkila, J., Myers, J. M., Stidham, B. J., & Hartmann, D. H. 1997, AJ, 114, 2043

Hoffleit, D., & Jaschek, C. 1982, The Bright Star Catalogue (4th ed.; New Haven: Yale Univ. Obs.)

Ivezic, Z., & Elitzur, M. 1995, ApJ, 445, 415

Jones, B., Merrill, K. M., Puetter, R. C., & Willner, S. P. 1978, AJ, 83, 1437

Joyce, R. R. 1998, AJ, 115, 2059

Kelly, D., & Latter, W. 1995, AJ, 109, 1320

Kerschbaum, F., & Hron, J. 1992, A&A, 263, 97

Koornneef, J. 1983, A&A, 128, 84

Kurucz, R. L. 1994, CD-ROM 19, Solar Abundance Model Atmosphere for 0, 1, 2, 4, 8 km/s (Cambridge: SAO)

Lancon, A., & Wood, P. 2000, A&AS, 146, 217

Lebofsky, M. J., & Rieke, G. H. 1977, AJ, 82, 646

Liebert, J., Cutri, R. M., Nelson, B., Kirkpatrick, J. D., & Gizis, J. E. 2000, PASP, 112, 1315

Little-Marinen, I. 1986, ApJ, 307, L15

Monet, D., et al. 1998, USNO-A V2.0: A Catalog of Astrometric Standards (Washington: US Naval Obs.)

Mutschke, H., Anderson, A. C., Clement, D., Henning, Th., & Peiter, G. 1999, A&A, 345, 187

Nikolaev, S., & Weinberg, M. D. 2000, ApJ, 542, 804

Rudy, R. J., Puetter, R. C., & Mazuk, S. 1999, AJ, 118, 666

Rudy, R. J., Venturini, C. C., Lynch, D. K., Mazuk, S., & Puetter, R. C. 2002, ApJ, 573, 794

Salpeter, E. E. 1974, ApJ, 193, 579

Skinner, C. J., & Griffin, I. P. 1989, MNRAS, 240, 189

Skrutskie, M. F., et al. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garson et al. (Dordrecht: Kluwer), 187

Speck, A. K., Barlow, M. J., & Skinner, C. J. 1997, MNRAS, 288, 431

Treffers, R. R., & Cohen, M. 1974, ApJ, 188, 545

Volk, K., Xiong, G.-Z., & Kwok, S. 2000, ApJ, 530, 408

Wallerstein, G., & Knapp, G. R. 1998, ARA&A, 36, 369