

---

# Chapter 7

---

## Infrared Astronomy

A.T. Tokunaga

---

7.1	Useful Equations; Units . . . . .	1
7.2	Atmospheric Transmission . . . . .	2
7.3	Background Emission . . . . .	4
7.4	Detectors and Signal-to-Noise Ratios . . . . .	5
7.5	Photometry ( $\lambda < 30 \mu\text{m}$ ) . . . . .	8
7.6	Photometry ( $\lambda > 30 \mu\text{m}$ ) . . . . .	12
7.7	Infrared Line List . . . . .	13
7.8	Dust . . . . .	17
7.9	Solar System . . . . .	20
7.10	Stars . . . . .	22
7.11	Extragalactic Objects . . . . .	23

---

### 7.1 USEFUL EQUATIONS; UNITS

The Planck function in wavelength units ( $\lambda_{\mu\text{m}}$  in  $\mu\text{m}$ ;  $T$  in K) is

$$\begin{aligned} B_{\lambda} &= 2hc^2\lambda^{-5}/(e^{hc/k\lambda T} - 1) \\ &= 1.1910 \times 10^8 \lambda_{\mu\text{m}}^{-5}/(e^{14.387.7/\lambda_{\mu\text{m}}T} - 1) \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}. \end{aligned}$$

The Planck function in frequency units ( $\nu$  in Hz) is

$$\begin{aligned} B_{\nu} &= 2h\nu^3c^{-2}/(e^{h\nu/kT} - 1) \\ &= 1.4745 \times 10^{-50} \nu^3/(e^{4.79922 \times 10^{-11} \nu/T} - 1) \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}. \end{aligned}$$

The Rayleigh–Jeans approximation (for  $h\nu \ll kT$ ) is

$$B_\lambda = 2ckT\lambda^{-4} = 8.2782 \times 10^3 T/\lambda_{\mu\text{m}}^4 \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1},$$

$$B_\nu = 2c^{-2}kT\nu^2 = 3.0724 \times 10^{-40} T\nu^2 \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}.$$

The Stefan–Boltzmann law is

$$B = \int B_\lambda d\lambda = (\sigma/\pi)T^4 = 1.8050 \times 10^{-8} T^4 \text{ W m}^{-2} \text{ sr}^{-1}.$$

The wavelength of maximum  $B_\lambda$  (Wien law) is

$$\lambda_{\text{max}} = 2898/T, \quad \lambda_{\text{max}} \text{ in } \mu\text{m}.$$

The frequency of maximum  $B_\nu$  is

$$\nu_{\text{max}} = 5.878 \times 10^{10} T, \quad \nu_{\text{max}} \text{ in Hz}.$$

The conversion equations ( $\Omega$  in sr) are  $F_\lambda = \Omega B_\lambda$ ,  $F_\nu = \Omega B_\nu$ ,  $F_\lambda = 3.0 \times 10^{14} F_\nu/\lambda_{\mu\text{m}}^2$ . Other units are 1 Jansky (Jy) =  $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ . Units details are given in Table 7.1.

**Table 7.1.** *Units [1–4].*

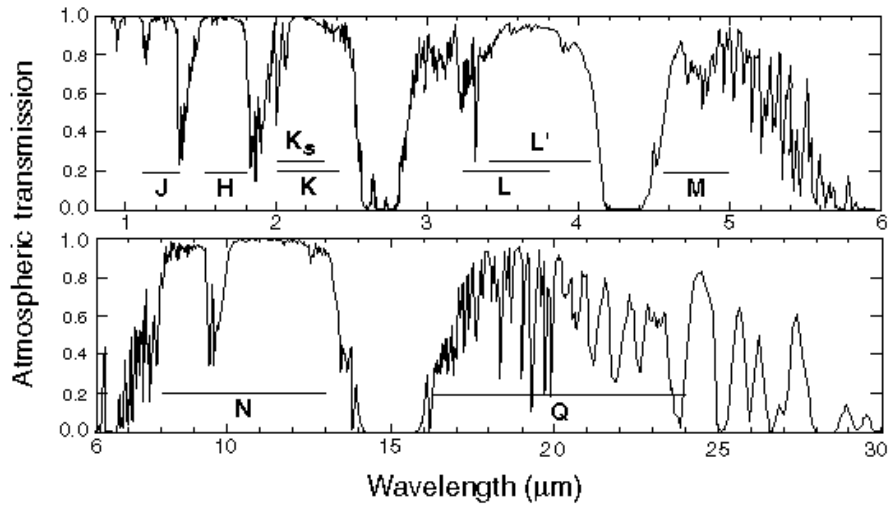
Units	Radiometric name	Astronomical name
W	Flux	Luminosity
$\text{W m}^{-2}$	Irradiance; radiant exitance	Flux
$\text{W sr}^{-1}$	Intensity	...
$\text{W m}^{-2} \text{ sr}^{-1}$	Radiance	Intensity
$\text{W m}^{-2} \mu\text{m}^{-1}$ ; $\text{W m}^{-2} \text{ Hz}^{-1}$	Spectral irradiance	Flux density
$\text{W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$ ; $\text{W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$	Spectral radiance	Surface brightness; specific intensity

#### References

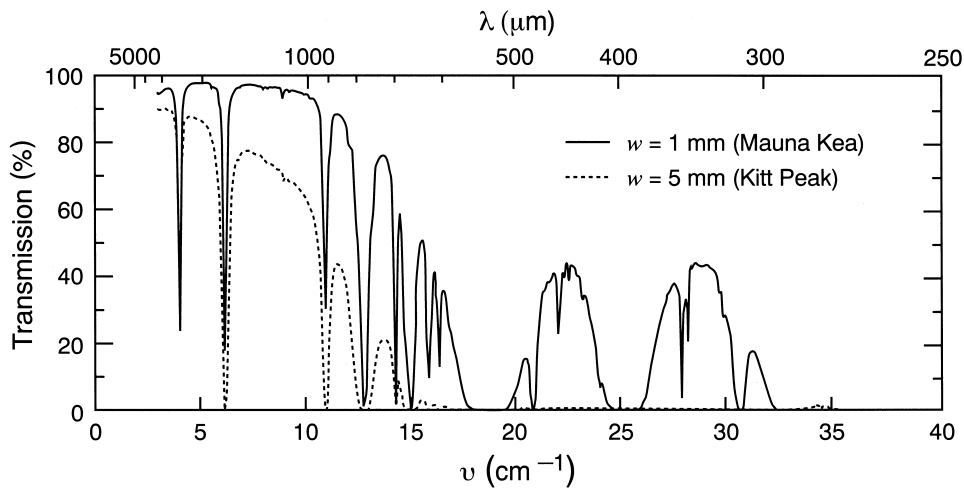
1. Boyd, R.W. 1983, *Radiometry and the Detection of Optical Radiation* (Wiley, New York)
2. Dereniak, E.L., & Crowe, D.G. 1984, *Optical Radiation Detectors* (Wiley, New York)
3. Wolfe, W.L., & Zissis, G.J. 1985, *The Infrared Handbook*, revised ed. (Office of Naval Research, Washington, D.C.)
4. Rieke, G.H. 1994, *Detection of Light; From the Ultraviolet to the Submillimeter* (Cambridge University Press, Cambridge)

## 7.2 ATMOSPHERIC TRANSMISSION

The major atmospheric absorbers and central wavelengths of absorption bands are  $\text{H}_2\text{O}$  (0.94, 1.13, 1.37, 1.87, 2.7, 3.2, 6.3,  $\lambda > 16 \mu\text{m}$ );  $\text{CO}_2$  (2.0, 4.3, 15  $\mu\text{m}$ );  $\text{N}_2\text{O}$  (4.5, 17  $\mu\text{m}$ );  $\text{CH}_4$  (3.3, 7.7  $\mu\text{m}$ );  $\text{O}_3$  (9.6  $\mu\text{m}$ ). See Figures 7.1 and 7.2.



**Figure 7.1.** Atmospheric transmission from 0.9 to 30  $\mu\text{m}$  under conditions appropriate for Mauna Kea, Hawaii. Altitude = 4.2 km, zenith angle =  $30^\circ$  (air mass = 1.15), precipitable water vapor overhead = 1 mm.  $\lambda/\Delta\lambda = 300$  for 1–6  $\mu\text{m}$  and 150 for 6–30  $\mu\text{m}$ . Spectra are calculated by Lord [1]. The infrared filter band passes are shown as horizontal lines; see Table 7.5 for definitions. Note that the filter transmission is modified by the atmospheric absorption. For the atmospheric transmission at Kitt Peak, see [2]. For ESO, see [3]. See also [4].



**Figure 7.2.** Atmospheric transmission from 0.25 to 3 mm, adapted from [5]. The precipitable water vapor is denoted by  $w$ . See also [6–9]. For the South Pole, see [10].

For atmospheric transmission at airborne and balloon altitudes see [6, 11]. For water-vapor measurements at observatory sites see [12–14]. For atmospheric extinction see [2, 15–17].

## 7.3 BACKGROUND EMISSION

### 7.3.1 Background Emission Sources

Table 7.2 gives the background emission from a ground-based telescope. The main background emission sources are shown in Figure 7.3. Where specified they are blackbody functions reduced by a multiplying factor  $\epsilon$ . In most cases, only the minimum background levels are plotted.

OH	OH airglow. Average OH emission of 15.6 and 13.8 magarcsec <sup>-2</sup> at J and H, respectively [18–21].
GBT	Ground-based telescope thermal emission, optimized for the thermal infrared and approximated as a 273-K blackbody with $\epsilon = 0.02$ . Emission from the Earth’s atmosphere at 1.5–25 $\mu\text{m}$ is shown [22].
ZSL	Zodiacal scattered light at the ecliptic pole, approximated as a 5800-K blackbody with $\epsilon = 3 \times 10^{-14}$ (based on data from [23]).
ZE	Zodiacal emission from interplanetary dust at the ecliptic pole, approximated as a 275-K blackbody with $\epsilon = 7.1 \times 10^{-8}$ . Based on observations from the Infrared Astronomical Satellite (IRAS) [24].
GBE	Galactic background emission from interstellar dust in the plane of the galaxy. In the plane of the Galaxy away from the Galactic Center, it can be approximated by a 17-K blackbody and $\epsilon = 10^{-3}$ [25, 26].
SEP	South ecliptic pole emission as measured by the Cosmic Background Explorer (COBE) spacecraft [27].
CST	Cryogenic space telescope, cooled to 10 K with $\epsilon = 0.05$ .
CBR	Cosmic background radiation, 2.73-K blackbody with $\epsilon = 1.0$ [28].

**Table 7.2.** Combined sky, telescope, and instrument background emission at the 3.0-m IRTF<sup>a</sup> [1].

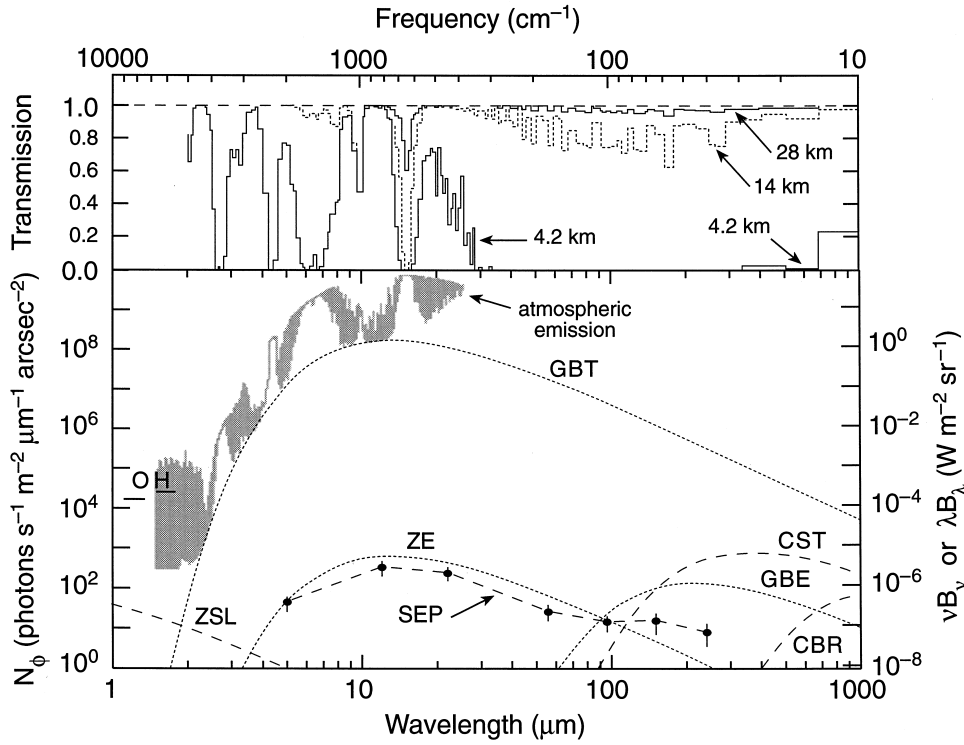
Band	$\lambda$ ( $\mu\text{m}$ )	$\Delta\lambda$	Surface brightness (mag arcsec <sup>-2</sup> )	Band	$\lambda$ ( $\mu\text{m}$ )	$\Delta\lambda$	Surface brightness (mag arcsec <sup>-2</sup> )
<i>J</i>	1.26	0.31	15.9	<i>L</i>	3.50	0.61	4.9
<i>H</i>	1.62	0.28	13.4	<i>L'</i>	3.78	0.59	4.5
<i>K<sub>s</sub></i>	2.15	0.35	14.1	<i>M'</i>	4.78	0.22	0.3
<i>K</i>	2.21	0.39	13.7	<i>M</i>	4.85	0.62	-0.7

**Note**

<sup>a</sup>Telescope emissivity at the time of the observations was about 7%.

**Reference**

1. Shure, M., *et al.* 1994, Proc. SPIE, **2198**, 614



**Figure 7.3.** Top: Transmission of the Earth's atmosphere at Mauna Kea (4.2 km), airborne (14 km), and balloon altitudes (28 km), adapted from [6]. Bottom: Background emission sources. The surface brightness is calculated from  $N_\phi = \epsilon \lambda_{\mu m} B_\lambda / (hc) = 1.41 \times 10^{16} \epsilon \lambda_{\mu m}^{-4} / (e^{14387.7/\lambda_{\mu m} T} - 1)$  ( $\lambda_{\mu m}$  in  $\mu m$ ,  $T$  in K). The intensity is derived from  $\lambda_{\mu m} B_\lambda = 8.45 \times 10^{-9} N_\phi$ .

### 7.3.2 OH Emission Spectrum

The OH emission is often given in Rayleigh units. To convert to other units, use the following equations, with  $\lambda_{\mu m}$  in  $\mu m$  [29]:

$$\begin{aligned}
 1 \text{ Rayleigh unit} &= 10^{10}/4\pi \text{ photons } s^{-1} m^{-2} sr^{-1} \\
 &= 1.5808 \times 10^{-10}/\lambda_{\mu m} \text{ W } m^{-2} sr^{-1}, \\
 1 \text{ Rayleigh unit}/\text{\AA} &= 1.5808 \times 10^{-6}/\lambda_{\mu m} \text{ W } m^{-2} \mu m^{-1} sr^{-1} \\
 &= 3.7184 \times 10^{-17}/\lambda_{\mu m} \text{ W } m^{-2} \mu m^{-1} arcsec^{-2}.
 \end{aligned}$$

The OH airglow spectrum is given in Figure 7.4.

## 7.4 DETECTORS AND SIGNAL-TO-NOISE RATIOS

Tables 7.3 and 7.4 list the basic detector types for infrared observations.

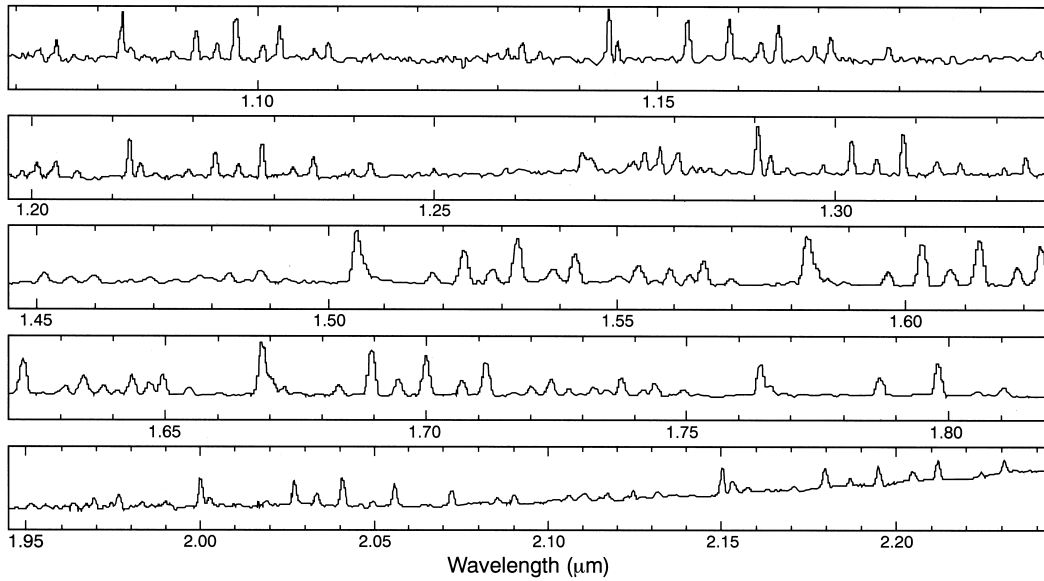


Figure 7.4. Observed OH airglow spectrum adapted from [30]. See also [19, 31–34, 29].

Table 7.3. Basic detector types and typical useful wavelength ranges [1–4].

Material	Type <sup>a</sup>	Wavelength range ( $\mu\text{m}$ ) <sup>b</sup>	Material	Type <sup>a</sup>	Wavelength range ( $\mu\text{m}$ ) <sup>b</sup>
Si	PD	<1.1	Si:Sb	IBC	14–38
Ge	PD	<1.8	Ge:Be	PC	30–50
HgCdTe	PD	1–2.5	Ge:Ga	PC	40–120
PtSi	SD	1–4	Ge:Ga	PC (stressed)	120–200
InSb	PD	1–5.6	Ge or Si	TD (bolometer)	200–1000
Si:As	IBC	6–27			

#### Notes

<sup>a</sup>PD=photodiode, PC=photoconductor, SD=Schottky diode, IBC=impurity band conduction photoconductor [also known as blocked impurity band (BIB) photoconductor]; TD=thermal detector.

<sup>b</sup>The HgCdTe long-wavelength cutoff is determined by the Hg/Cd ratio and can be extended to 25  $\mu\text{m}$ .

#### References

1. Rieke, G.H. 1994, *Detection of Light: From the Ultraviolet to the Submillimeter* (Cambridge University Press, Cambridge)
2. Fazio, G.G. 1994, *Infrared Phys. Technol.*, **35**, 107
3. Herter, T. 1994, in *Infrared Astronomy with Arrays*, ed. I. McLean (Kluwer, Dordrecht), p. 409
4. Haller, E.E. 1994, *Infrared Phys. Technol.*, **35**, 127

For an object that is distributed over  $n$  pixels, the signal photocurrent for photodiodes, photoconductors, and Schottky diodes is [35]

$$\sum_n i_s = A\tau\eta G\lambda F_\lambda \Delta\lambda/(hc) = A\tau\eta G(\Delta\lambda/\lambda)F_\nu/h \text{ electrons s}^{-1},$$

where  $i_s$  is the photocurrent from an individual pixel,  $A$  ( $\text{m}^2$ ) is the telescope collecting area,  $\tau$  is the transmission of instrument, telescope, and atmosphere,  $\eta$  is the detector quantum efficiency,  $G$  is the photoconductive gain ( $=1$  for a photodiode;  $\leq 0.5$  for a photoconductor),  $\Delta\lambda/\lambda$  is the fractional spectral bandwidth,  $F_\lambda$  ( $\text{W m}^{-2} \mu\text{m}^{-1}$ ) $=\Omega_{\text{source}}B_\lambda$  = source flux density, and  $F_\nu$  ( $\text{W m}^{-2} \text{Hz}^{-1}$ ) $=\Omega_{\text{source}}B_\nu$  = source flux density.

The background photocurrent per pixel is

$$i_{\text{bg}} = A\tau\eta GN_\phi\Delta\lambda\Omega_{\text{pix}} \text{ electrons s}^{-1},$$

where  $N_\phi$  ( $\text{photons s}^{-1} \text{m}^{-2} \mu\text{m}^{-1} \text{arcsec}^{-2}$ ) is the background surface brightness and  $\Omega_{\text{pix}}$  ( $\text{arcsec}^2$ ) is the solid angle on the sky viewed by one pixel.

The RMS noise per pixel is

$$[N_r^2 + xG(i_s + i_{\text{bg}} + i_{\text{dc}})t]^{1/2} \text{ electrons},$$

where  $N_r$  (electrons) is the detector read noise,  $i_{\text{dc}}$  ( $\text{electrons s}^{-1}$ ) is the detector dark current,  $t$  (s) is the integration time, and  $x=1$  for a photodiode or IBC photoconductor or  $x=2$  for a photoconductor.

The signal-to-noise ratio before sky subtraction is

$$S/N = \left( \sum_n i_s \right) t \left( \sum_n [N_r^2 + xG(i_s + i_{\text{bg}} + i_{\text{dc}})t] \right)^{-1/2}.$$

An alternative signal-to-noise ratio equation including the noise introduced by sky subtraction is [36]:

$$S/N = N_{\text{obj}} \left[ N_{\text{obj}} + n_{\text{pix}}(1 + n_{\text{pix}}/n_{\text{bg}})(N_r^2 + N_{\text{bg}} + N_{\text{dc}} + N_{\text{dig}}^2) \right]^{-1/2},$$

where  $N_{\text{obj}}$  is the total number of signal electrons from the object ( $=\sum i_s t$ ),  $n_{\text{pix}}$  is the number of pixels summed for the object,  $n_{\text{bg}}$  is the number of pixels summed for the sky subtraction,  $N_r$  is the read noise in electrons per pixel,  $N_{\text{bg}}$  is the sky background in electrons per pixel ( $=xGi_{\text{bg}}t$ ),  $N_{\text{dc}}$  is the dark current in electrons per pixel ( $=xGi_{\text{dc}}t$ ), and  $N_{\text{dig}}$  is the digitization noise in electrons per pixel (usually negligible).

**Table 7.4.** *Far-infrared heterodyne detectors [1,2].*

Type	Wavelength range ( $\mu\text{m}$ )
Schottky diode	100–300
Superconducting–insulator–superconducting (SIS)	300–3000

#### References

1. Phillips, T.G. 1988, in *Millimetre and Submillimetre Astronomy*, ed. R. D. Wolstencroft & W. B. Burton (Kluwer, Dordrecht), p. 1
2. White, G.J. 1988, in *Millimetre and Submillimetre Astronomy*, ed. R. D. Wolstencroft & W. B. Burton (Kluwer, Dordrecht), p. 27

For a heterodyne receiver [37],

$$S/N = (T_S/T_N) \sqrt{t \Delta\nu},$$

where  $T_S$  is the source temperature (K),  $T_N$  is the equivalent Rayleigh–Jeans noise temperature (K) of the receiver, and  $\Delta\nu$  (Hz) is the channel width of the radio integrator.

## 7.5 PHOTOMETRY ( $\lambda < 30 \mu\text{m}$ )

There is no common infrared photometric (radiometric) system. As a result, filter central wavelengths, filter bandwidths, and instrumental responses are different at each observatory, as are the effects of the atmospheric transmission. The flux density of Vega established by Cohen *et al.* [38] is presented in Table 7.5. It is based upon an atmospheric model for Vega and the flux density calibration at  $0.5556 \mu\text{m}$  given by Hayes [39]. It is consistent with ground-based absolute flux density measurements to within  $\leq 2\sigma$  of the measurement errors.

**Table 7.5.** Filter wavelengths, bandwidths, and flux densities for Vega.<sup>a</sup>

Filter name	$\lambda_{\text{iso}}^b$ ( $\mu\text{m}$ )	$\Delta\lambda^c$ ( $\mu\text{m}$ )	$F_\lambda$ ( $\text{W m}^{-2} \mu\text{m}^{-1}$ )	$F_\nu$ (Jy)	$N_\phi$ (photons $\text{s}^{-1} \text{m}^{-2} \mu\text{m}^{-1}$ )
V	0.5556 <sup>d</sup>	...	$3.44 \times 10^{-8}$	3540	$9.60 \times 10^{10}$
J	1.215	0.26	$3.31 \times 10^{-9}$	1630	$2.02 \times 10^{10}$
H	1.654	0.29	$1.15 \times 10^{-9}$	1050	$9.56 \times 10^9$
$K_s$	2.157	0.32	$4.30 \times 10^{-10}$	667	$4.66 \times 10^9$
K	2.179	0.41	$4.14 \times 10^{-10}$	655	$4.53 \times 10^9$
L	3.547	0.57	$6.59 \times 10^{-11}$	276	$1.17 \times 10^9$
$L'$	3.761	0.65	$5.26 \times 10^{-11}$	248	$9.94 \times 10^8$
M	4.769	0.45	$2.11 \times 10^{-11}$	160	$5.06 \times 10^8$
8.7	8.756	1.2	$1.96 \times 10^{-12}$	50.0	$8.62 \times 10^7$
N	10.472	5.19	$9.63 \times 10^{-13}$	35.2	$5.07 \times 10^7$
11.7	11.653	1.2	$6.31 \times 10^{-13}$	28.6	$3.69 \times 10^7$
Q	20.130	7.8	$7.18 \times 10^{-14}$	9.70	$7.26 \times 10^6$

### Notes

<sup>a</sup>Cohen *et al.* [1] recommend the use of Sirius rather than Vega as the photometric standard for  $\lambda > 20 \mu\text{m}$  because of the infrared excess of Vega at these wavelengths. The magnitude of Vega depends on the photometric system used, and it is either assumed to be 0.0 mag. or assumed to be 0.02 or 0.03 mag. for consistency with the visual magnitude.

<sup>b</sup>The infrared isophotal wavelengths and flux densities (except for  $K_s$ ) are taken from Table 1 of [1], and they are based on the UKIRT filter set and the atmospheric absorption at Mauna Kea. See Table 2 of [1] for the case of the atmospheric absorption at Kitt Peak. The isophotal wavelength is defined by  $F(\lambda_{\text{iso}}) = \int F(\lambda)S(\lambda) d\lambda / \int S(\lambda) d\lambda$ , where  $F(\lambda)$  is the flux density of Vega and  $S(\lambda)$  is the (detector quantum efficiency)  $\times$  (filter transmission)  $\times$  (optical efficiency)  $\times$  (atmospheric transmission)[2].  $\lambda_{\text{iso}}$  depends on the spectral shape of the source and a correction must be applied for broadband photometry of sources that deviate from the spectral shape of the standard star [3]. The flux density and  $\lambda_{\text{iso}}$  for  $K_s$  were calculated here. For the  $K'$  filter, see [4].

<sup>c</sup>The filter full width at half maximum.

<sup>d</sup>The wavelength at V is a monochromatic wavelength; see [5].

### References

1. Cohen, M., *et al.* 1992, AJ, **104**, 1650



2. Golay, M. 1974, *Introduction to Astronomical Photometry* (Reidel, Dordrecht), p. 40
3. Hanner, M.S., *et al.* 1984, *AJ*, **89**, 162
4. Wainscoat, R.J., & Cowie, L.L. 1992, *AJ*, **103**, 332
5. Hayes, D.S. 1985, in *Calibration of Fundamental Stellar Quantities*, ed. D. S. Hayes, *et al.*, Proc. IAU Symp. No. 111 (Reidel, Dordrecht), p. 225

*Absolute calibration.* (a) For 1.2–5  $\mu\text{m}$ , see [40]. (b) For 10–20  $\mu\text{m}$ , see [41].

*Photometric systems and standard star observations.* For AAO, 1.2–3.8  $\mu\text{m}$ , see [42]; for CIT, 1.2–3.5  $\mu\text{m}$ , see [43]; for ESO, 1.2–3.8  $\mu\text{m}$ , see [44]; for ESO, 1.2–4.8  $\mu\text{m}$ , see [45]; for IRTF, 10–20  $\mu\text{m}$ , see [46]; for KPNO, 1.2–2.2  $\mu\text{m}$ , see [47]; for MSO, 1.2–2.2  $\mu\text{m}$ , see [48]; for OAN, 1.2–2.2  $\mu\text{m}$ , see [49]; for SAAO, 1.2–3.4  $\mu\text{m}$ , see [50]; for UA, IRTF, WIRO, 1.2–20  $\mu\text{m}$ , see [51]; for UKIRT, 1–2.2  $\mu\text{m}$ , faint standards, see [52]; for WIRO, 1.2–33  $\mu\text{m}$ , see [53].

*Color transformations.* For JHKLL/M; SAAO–Johnson, SAAO–ESO, SAAO–AAO, AAO–MSO, AAO–CIT, see [17]; for JHKLM; ESO–SAAO; ESO–AAO; ESO–MSSSO; ESO–CTIO, see [44]; for JHK; OAN–CIT, OAN–AAO, OAN–ESO, OAN–Johnson, see [49]; for JHKL; SAAO–ESO, SAAO–AAO, SAAO–MSSSO, SAAO–CTIO, see [50]; for JHKL; CIT–AAO, CIT–SAAO, CIT–Johnson, see [54]; for JHKLM; Johnson–ESO, Johnson–SAAO, see [55]; for JHK; CIT–IRTF, CIT–UKIRT, CIT–CTIO, CIT–ESO, CIT–KPNO, CIT–HCO, CIT–AAO, CIT–Johnson/Glass, see [56].

*Acronyms.* AAO=Anglo-Australian Observatory; CIT=California Institute of Technology; CTIO=Cerro Tololo Inter-American Observatory; ESO=European Southern Observatory; HCO=Harvard College Observatory (Mt. Hopkins); IRTF=NASA Infrared Telescope Facility; KPNO=Kitt Peak National Observatory; MSO=Mt. Stromlo Observatory; MSSSO=Mt. Stromlo/Siding Springs Observatory; OAN=San Pedro Mártir National Observatory; SAAO=South African Astronomical Observatory; UA=University of Arizona; UKIRT=United Kingdom Infrared Telescope; WIRO=Wyoming Infrared Observatory.

Tables 7.6–7.8 give intrinsic colors and effective temperatures for stars.

**Table 7.6.** *Intrinsic colors and effective temperatures for the main sequence (class V).<sup>a</sup>*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$K - L'$	$K - M$	$T_{\text{eff}}^b$
O9	-0.87	-0.14	-0.04	-0.06			35 900
O9.5	-0.85	-0.13	-0.04	-0.06			34 600
B0	-0.83	-0.12	-0.04	-0.06			31 500
B1	-0.74	-0.10	-0.03	-0.05			25 600
B2	-0.66	-0.09	-0.03	-0.05			22 300
B3	-0.56	-0.08	-0.02	-0.05			19 000
B4	-0.49	-0.07	-0.02	-0.05			17 200
B5	-0.42	-0.06	-0.01	-0.04			15 400
B6	-0.36	-0.05	-0.01	-0.04			14 100
B7	-0.29	-0.03	-0.01	-0.04			13 000
B8	-0.24	-0.03	0.00	-0.04			11 800
B9	-0.13	-0.01	0.00	-0.03			10 700
A0	0.00	0.00	0.00	0.00	0.00	0.00	9 480
A2	0.14	0.02	0.01	0.01	0.01	0.01	8 810
A5	0.38	0.06	0.02	0.02	0.02	0.03	8 160
A7	0.50	0.09	0.03	0.03	0.03	0.03	7 930
F0	0.70	0.13	0.03	0.03	0.03	0.03	7 020
F2	0.82	0.17	0.04	0.03	0.03	0.03	6 750
F5	1.10	0.23	0.04	0.04	0.04	0.02	6 530
F7	1.32	0.29	0.05	0.04	0.04	0.02	6 240

**Table 7.6.** *Continued.*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$K - L'$	$K - M$	$T_{\text{eff}}^b$
G0	1.41	0.31	0.05	0.05	0.05	0.01	5930
G2	1.46	0.32	0.05	0.05	0.05	0.01	5830
G4	1.53	0.33	0.06	0.05	0.05	0.01	5740
G6	1.64	0.37	0.06	0.05	0.05	0.00	5620
K0	1.96	0.45	0.08	0.06	0.06	-0.01	5240
K2	2.22	0.50	0.09	0.07	0.07	-0.02	5010
K4	2.63	0.58	0.11	0.09	0.10	-0.04	4560
K5	2.85	0.61	0.11	0.10	0.11		4340
K7	3.16	0.66	0.15	0.11	0.13		4040
M0	3.65	0.67	0.17	0.14	0.17		3800
M1	3.87	0.66	0.18	0.15	0.21		3680
M2	4.11	0.66	0.20	0.16	0.23		3530
M3	4.65	0.64	0.23	0.20	0.32		3380
M4	5.28	0.62	0.27	0.23	0.37		3180
M5	6.17	0.62	0.33	0.29	0.42		3030
M6	7.37	0.66	0.38	0.36	0.48		2850

**Notes**

<sup>a</sup>Colors given in the Johnson–Glass system as established by Bessell and Brett [1]. References used: O,B, [2]; A,F,G,K, [1]; K,M, [3]. Did not use K–M from [2] because there is a large offset compared to [1]. Approximate uncertainties (one standard deviation):  $\pm 0.02$  (O–K);  $\pm 0.03$  (M).

<sup>b</sup> $T_{\text{eff}}$  is an average of values from the following sources: for O,B, [4]; for B,A,F,G,K, [5]; for B,G,K, [6]; for A,F, [7]; for A,F,G,K, [8]; for A,F,G, [9]; for G,K, [10]; for K,M, [3]; for M, [11],[7],[12]. Approximate uncertainties (one standard deviation):  $\pm 1000$  K (O9–B2);  $\pm 250$  K (B3–B9);  $\pm 100$  K (A0–M6).

**References**

1. Bessell, M.S., & Brett, J.M. 1988, PASP, **100**, 1134
2. Koornneef, J. 1983, A&A, **128**, 84
3. Bessell, M.S. 1991, AJ, **101**, 662
4. Vacca, W.D., *et al.* 1996, ApJ, **460**, 914
5. Popper, D.M. 1980, ARA&A, **18**, 115
6. Böhm-Vitense, E. 1981, ARA&A, **19**, 295
7. Böhm-Vitense, E. 1982, ApJ, **255**, 191
8. Blackwell, D.E., *et al.* 1991, A&A, **245**, 567
9. Fernley, J.A. 1989, MNRAS, **239**, 905
10. Bell, R.A., & Gustafsson, B. 1989, MNRAS, **236**, 653
11. Jones, H.R.A., *et al.* 1995, MNRAS, **277**, 767
12. Leggett, S.K., *et al.* 1996, ApJS, **104**, 117

**Table 7.7.** *Intrinsic colors and effective temperatures for giant stars (class III).<sup>a</sup>*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$K - L'$	$K - M$	$T_{\text{eff}}^b$
G0	1.75	0.37	0.07	0.04	0.05	0.00	5910
G4	2.05	0.47	0.08	0.05	0.06	-0.01	5190
G6	2.15	0.50	0.09	0.06	0.07	-0.02	5050
G8	2.16	0.50	0.09	0.06	0.07	-0.02	4960
K0	2.31	0.54	0.10	0.07	0.08	-0.03	4810
K1	2.50	0.58	0.10	0.08	0.09	-0.04	4610
K2	2.70	0.63	0.12	0.09	0.10	-0.05	4500
K3	3.00	0.68	0.14	0.10	0.12	-0.06	4320
K4	3.26	0.73	0.15	0.11	0.14	-0.07	4080
K5	3.60	0.79	0.17	0.12	0.16	-0.08	3980

**Table 7.7.** *Continued.*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$K - L'$	$K - M$	$T_{\text{eff}}^b$
M0	3.85	0.83	0.19	0.12	0.17	-0.09	3820
M1	4.05	0.85	0.21	0.13	0.17	-0.10	3780
M2	4.30	0.87	0.22	0.15	0.19	-0.12	3710
M3	4.64	0.90	0.24	0.17	0.20	-0.13	3630
M4	5.10	0.93	0.25	0.18	0.21	-0.14	3560
M5	5.96	0.95	0.29	0.20	0.22	-0.15	3420
M6	6.84	0.96	0.30				3250
M7	7.80	0.96	0.31				

**Notes**

<sup>a</sup>Colors given in the Johnson–Glass system as established by Bessell and Brett in [1]. Approximate uncertainties (one standard deviation):  $\pm 0.02$ .

<sup>b</sup> $T_{\text{eff}}$  is an average of values from the following sources: for G,K,M, [2]; for K,M, [3]; for G,K, [4]; for G,K,M, [5]. Approximate uncertainties (one standard deviation):  $\pm 50$  K (G2–K5);  $\pm 70$  K (M0–M6). For O and B stars, see [6].

**References**

1. Bessell, M.S., & Brett, J.M. 1988, *PASP*, **100**, 1134
2. Ridgway, S.T., *et al.* 1980, *ApJ*, **235**, 126
3. Di Benedetto, G.P., & Rabbia, Y. 1987, *A&A*, **188**, 114
4. Bell, R.A., & Gustafsson, B. 1989, *MNRAS*, **236**, 653
5. Blackwell, D.E., *et al.* 1991, *A&A*, **245**, 567
6. Vacca, W.D., *et al.* 1996, *ApJ*, **460**, 914

**Table 7.8.** *Intrinsic colors and effective temperatures for supergiant stars (class I).<sup>a</sup>*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$T_{\text{eff}}^b$
O9	-0.82	-0.05	-0.13	-0.08	32500
B0	-0.69	-0.04	-0.10	-0.07	26000
B1	-0.55	-0.03	-0.06	-0.07	20700
B2	-0.40	-0.04	0.00	-0.07	17800
B3	-0.28	-0.03	0.03	-0.05	15600
B4	-0.20	-0.01	0.01	-0.01	13900
B5	-0.13	0.01	0.00	0.02	13400
B6	-0.07	0.04	-0.02	0.03	12700
B7	0.01	0.06	-0.02	0.04	12000
B8	0.07	0.07	-0.02	0.05	11200
B9	0.13	0.08	-0.02	0.06	10500
A0	0.19	0.09	-0.02	0.07	9730
A1	0.26	0.11	-0.01	0.07	9230
A2	0.32	0.12	-0.01	0.08	9080
A5	0.48	0.13	0.02	0.07	8510
F0	0.64	0.15	0.04	0.06	7700
F2	0.75	0.18	0.05	0.06	7170
F5	0.93	0.22	0.06	0.07	6640
F8	1.21	0.28	0.07	0.07	6100
G0	1.44	0.33	0.08	0.08	5510
G3	1.67	0.38	0.09	0.08	4980
G8	1.99	0.43	0.11	0.09	4590
K0	2.15	0.46	0.12	0.10	4420
K1	2.28	0.49	0.13	0.11	4330

**Table 7.8.** *Continued.*

Spectral type	$V - K$	$J - H$	$H - K$	$K - L$	$T_{\text{eff}}^b$
K2	2.43	0.52	0.13	0.12	4 260
K3 Iab	2.90	0.59	0.13	0.15	4 130
K5 Iab	3.50	0.67	0.14	0.18	3 850
M0 Iab	3.80	0.73	0.18	0.20	3 650
M1 Iab	3.90	0.73	0.20	0.22	3 550
M2 Iab	4.10	0.73	0.22	0.24	3 450
M3 Iab	4.60	0.74	0.24	0.26	3 200
M4 Iab	5.20	0.78	0.26	0.28	2 980
M0 Ib	3.80	0.76	0.18	0.12	
M1 Ib	3.90	0.76	0.20	0.14	
M2 Ib	4.10	0.76	0.22	0.16	
M3 Ib	4.60	0.77	0.24	0.18	
M4 Ib	5.20	0.81	0.26	0.20	
M0 Ia	3.80	0.61	0.18	0.27	
M1 Ia	3.90	0.61	0.20	0.29	
M2 Ia	4.10	0.61	0.22	0.31	
M3 Ia	4.60	0.62	0.24	0.33	
M4 Ia	5.20	0.66	0.26	0.35	

**Notes**

<sup>a</sup>Colors given in the Johnson–Glass system as established by Bessell and Brett [1]. References used: For O,A, [2]; for A,F,G,K, [3]; for K,M, [4]. Approximate uncertainties (one standard deviation):  $\pm 0.03$ .

<sup>b</sup> $T_{\text{eff}}$  is an average of values from the following references: For O–M, [5]; for O–K, [6]; for O,B, [7]. Approximate uncertainties (one standard deviation):  $\pm 1000$  K (O9–B2);  $\pm 250$  K (B3–B9);  $\pm 200$  K (A–M).

**References**

1. Bessell, M.S., & Brett, J.M. 1988, *PASP*, **100**, 1134
2. Whittet, D.C.B., & van Breda, I.G. 1980, *MNRAS*, **192**, 467
3. Koornneef, J. 1983, *A&A*, **128**, 84
4. Elias, J., *et al.* 1985, *ApJS*, **57**, 91
5. Schmidt-Kaler, Th. 1982, in Landolt-Börnstein, New Series, ed. K. Schaifer & H. H. Voigt (Springer, Berlin), Vol. VI/2b, p. 451
6. Böhm-Vitense, E. 1981, *ARA&A*, **19**, 295
7. Remie, H., & Lamers, H.J.G.L.M. 1982, *A&A*, **105**, 85

**7.6 PHOTOMETRY ( $\lambda > 30 \mu\text{m}$ )**

The primary flux density calibrator for ground-based submillimeter and millimeter observations is Mars [57]. The main secondary calibrators are Uranus [58, 59] and Jupiter [5, 59, 60]. Other secondary calibrators consist of astronomical sources [59, 61].

Instrument details for the IRAS satellite are given in Table 7.9.

**Table 7.9.** *Infrared Astronomical Satellite (IRAS) summary information.*<sup>a</sup>

Effective wavelength ( $\mu\text{m}$ )	12	25	60	100
Bandwidth (FWHM) ( $\mu\text{m}$ )	7.0	11.15	32.5	31.5
Typical detector field of view, (in scan) $\times$ (cross scan) (arcmin)	0.76 $\times$ 4.55	0.76 $\times$ 4.65	1.51 $\times$ 4.75	3.03 $\times$ 5.05
Point Source Catalog, with 2 coverages,				

**Table 7.9. Continued.**

Effective wavelength ( $\mu\text{m}$ )	12	25	60	100
90% completeness limits (Jy) <sup>b</sup>	0.45	...	0.64	...
Faint Source Catalog median 90% completeness limits (Jy) <sup>b</sup>	0.18	0.29	0.26	...

**Notes**

<sup>a</sup>IRAS observations are sensitive to dust with  $T > 25$  K. For IRAS catalogs, see [1,2].

<sup>b</sup>Completeness limits vary according to the amount of sky coverage obtained.

**References**

1. Infrared Astronomical Satellite (IRAS) Catalogs and Atlases, 1988, ed. Joint IRAS Science Working Group (U.S. Government Printing Office, Washington, D.C.), Vol. 1-7
2. The Infrared Processing & Analysis Center (IPAC) WWW Home Page (<http://www.ipac.caltech.edu/>) has numerous databases and information on IRAS catalogs

The following formulas give the IRAS four-band and two-band fluxes. For galactic sources [62]

$$F_{\text{ir}}(7 - 135 \mu\text{m}) = 1.0 \times 10^{-14} (20.653f_{12} + 7.538f_{25} + 4.578f_{60} + 1.762f_{100}) \text{ W m}^{-2}.$$

For extragalactic sources [63, 64]

$$F_{\text{ir}}(8 - 1000 \mu\text{m}) = 1.8 \times 10^{-14} (13.48f_{12} + 5.16f_{25} + 2.58f_{60} + f_{100}) \text{ W m}^{-2},$$

$$F_{\text{fir}}(43 - 123 \mu\text{m}) = 1.26 \times 10^{-14} (2.58f_{60} + f_{100}) \text{ W m}^{-2},$$

where  $f_{12}$ ,  $f_{25}$ ,  $f_{60}$ , and  $f_{100}$  are the IRAS flux densities in Jy at 12, 25, 60, and 100  $\mu\text{m}$ . These formulas are approximations based on assumptions about the intrinsic source spectrum and dust emissivity. It is recommended that the original references be consulted for details.

The luminosity (in solar luminosities) is

$$L_{\text{ir,fir}} = 3.127 \times 10^7 D^2 F_{\text{ir,fir}} L_{\odot},$$

where  $D$  is in pc and  $F_{\text{ir,fir}}$  is in  $\text{W m}^{-2}$ .

The far-infrared emission–radio emission correlation [65] is

$$q = \log\{[F_{\text{fir}}/(3.75 \times 10^{12} \text{ Hz})]/f_{1.4 \text{ GHz}}\} = 2.14,$$

where  $f_{1.4 \text{ GHz}}$  is the 1.4-GHz flux density in  $\text{W m}^{-2} \text{ Hz}^{-1}$ .

## 7.7 INFRARED LINE LIST

Table 7.10 presents data for a sample of infrared lines.

Table 7.10. Selected infrared lines.

$\lambda$ ( $\mu\text{m}$ ) <sup>a</sup>	$\nu$ ( $\text{cm}^{-1}$ ) <sup>a</sup>	Species	Transition <sup>b</sup>	Reference <sup>c</sup>
1.00521	9948.17	H I	$n=7-3$ (Pa $\delta$ )	[1,2,3]
1.01264	9875.18	He II	$n=5-4$	[1,3]
1.0833	9231.2	He I	$2p^3P^o-2s^3S$	[1,3]
1.09411	9139.85	H I	$n=6-3$ (Pa $\gamma$ )	[1,2,3]
1.11286	8985.84	Fe II	$b^4G_{5/2}-z^4F_{3/2}$	[4,5,6]
1.1290	8857.4	O I	$3d^3D^o-3p^3P$	[2,3,4]
1.16296	8598.75	He II	$n=7-5$	[1,3]
1.16764	8564.28	He II	$n=11-6$	[1,7]
1.252	7987.0	[Si IX]	$^3P_1 - ^3P_2$	[8,9,10,11]
1.25702	7955.30	[Fe II]	$a^4D_{7/2}-a^6D_{9/2}$	[4,5,6]
1.28216	7799.34	H I	$n=5-3$ (Pa $\beta$ )	[1,2,3]
1.31682	7594.03	O I	$4s^3S^o-3p^3P$	[3,6]
1.47644	6773.05	He II	$n=9-6$	[1,3]
1.52647	6551.08	H I	$n=19-4$ (Br19)	[1,2,3]
1.58848	6295.29	H I	$n=14-4$ (Br14)	[1,2,3]
1.61137	6205.92	H I	$n=13-4$ (Br13)	[1,2,3]
1.6189	6177.0	CO	$v = 6-3$ band head	[12]
1.62646	6148.32	OH	$v=2-0 P_{1d}(15)$	[12]
1.64117	6093.21	H I	$n=12-4$ (Br12)	[1,2,3]
1.64400	6082.73	[Fe II]	$a^4D_{7/2}-a^4F_{9/2}$	[4,5,6]
1.68111	5948.45	H I	$n=11-4$ (Br11)	[1,2,3]
1.68778	5924.94	Fe II	$c^4F_{9/2}-z^4F_{9/2}$	[4,5,6]
1.69230	5909.12	He II	$n=12-7$	[1,7]
1.70076	5879.74	He I	$4d^3D - 3p^3P^o$	[3,6]
1.73669	5758.08	H I	$n=10-4$ (Br10)	[1,2,3]
1.74188	5740.94	Fe II	$c^4F_{7/2}-z^4D_{7/2}$	[3,6]
1.81791	5500.82	H I	$n=9-4$ (Br9)	[1,2,3]
1.87561	5331.60	H I	$n=4-3$ (Pa $\alpha$ )	[2,3]
1.94509	5141.15	H I	$n=8-4$ (Br $\delta$ )	[1,2,3]
1.95756	5108.40	H <sub>2</sub>	$v=1-0 S(3)$	[13,14]
1.9634	5093.2	[Si VI]	$^2P_{1/2}-^2P_{3/2}$	[9,10,15]
2.03376	4917.01	H <sub>2</sub>	$v=1-0 S(2)$	[14,16]
2.040	4902.0	[Al IX]	$^2P_{3/2}^o-^2P_{1/2}^o$	[9,10]
2.04065	4900.39	H <sub>3</sub> <sup>+</sup>	$v=2\nu_2(2)-0; (4,6,+2)-(3,3)$	[17]
2.05869	4857.45	He I	$2p^1P^o-2s^1S$	[3,18]
2.06059	4852.99	Fe II	$c^4F_{5/2}-z^4F_{3/2}$	[5,6,18]
2.08938	4786.11	Fe II	$c^4F_{3/2}-z^4F_{3/2}$	[5,6,16]
2.09326	4777.23	H <sub>3</sub> <sup>+</sup>	$v=2\nu_2(2)-0; (7,9,+2)-(6,6)$	[17]
2.1127	4733.4	He I	$4s^3S-3p^3P^o$	[3,6]
2.12183	4712.91	H <sub>2</sub>	$v=1-0 S(1)$	[14,16]
2.13748	4678.41	Mg II	$5p^2P_{3/2}^o-5s^2S_{1/2}$	[18]
2.14380	4664.61	Mg II	$5p^2P_{1/2}^o-5s^2S_{1/2}$	[18]
2.16612	4616.55	H I	$n=7-4$ (Br $\gamma$ )	[2,3,16]
2.18911	4568.07	He II	$n=10-7$	[1,7]
2.20624	4532.59	Na I	$4p^2P_{3/2}^o-4s^2S_{1/2}$	[16,19,20]
2.20897	4527.00	Na I	$4p^2P_{1/2}^o-4s^2S_{1/2}$	[16,19,20]
2.22329	4497.84	H <sub>2</sub>	$v=1-0 S(0)$	[14,16]
2.24772	4448.96	H <sub>2</sub>	$v=2-1 S(1)$	[14,16]
2.26311	4418.69	Ca I	$4f^3F_3^o-4d^3D_2$	[19]
2.26573	4413.58	Ca I	$4f^3F_4^o-4d^3D_3$	[19]
2.29353	4360.09	CO	$v=2-0$ band head	[16]
2.32265	4305.42	CO	$v=3-1$ band head	[16]
2.34327	4267.54	CO	$v=2-0 R(1)$	[21]
2.34531	4263.84	CO	$v=2-0 R(0)$	[21]
2.34950	4256.22	CO	$v=2-0 P(1)$	[21]
2.35167	4252.30	CO	$v=2-0 P(2)$	[21]

Table 7.10. *Continued.*

$\lambda$ ( $\mu\text{m}$ ) <sup>a</sup>	$\nu$ ( $\text{cm}^{-1}$ ) <sup>a</sup>	Species	Transition <sup>b</sup>	Reference <sup>c</sup>
2.35246	4250.87	CO	$v=4-2$ band head	[16]
2.38295	4196.48	CO	$v=5-3$ band head	[16]
2.40659	4155.25	H <sub>2</sub>	$v=1-0$ Q(1)	[13,14]
2.41344	4143.47	H <sub>2</sub>	$v=1-0$ Q(2)	[13,14]
2.42373	4125.87	H <sub>2</sub>	$v=1-0$ Q(3)	[13,14]
2.4833	4026.9	[Si VII]	$^3P_1-^3P_2$	[9,10,15]
2.49995	4000.08	H <sub>2</sub>	$v=1-0$ Q(7)	[14,22]
2.62587	3808.26	H I	$n=6-4$ (Br $\beta$ )	[2,22]
2.62688	3806.80	H <sub>2</sub>	$v=1-0$ O(2)	[14,22]
3.0279	3302.6	[Mg VIII]	$^2P_{3/2}^o-^2P_{1/2}^o$	[8,9,10,15]
3.03920	3290.34	H I	$n=10-5$ (Pfe)	[2]
3.09169	3234.48	He II	$n=7-6$	[3]
3.133	3192.0	OH	$v=1-0$ , K=9 multiplet	[23]
3.29699	3033.07	H I	$n=9-5$ (Pfd)	[2,24]
3.41884	2924.97	He II	$n=25-11$	[3,24]
3.48401	2870.26	He II	$n=17-10$	[3,24]
3.50116	2856.20	H I	$n=24-6$ (Hu24)	[2,24]
3.52203	2839.27	H I	$n=23-6$ (Hu23)	[2,24]
3.6246	2758.9	H <sub>2</sub>	$v=0-0$ S(15)	[25,26]
3.64592	2742.79	H I	$n=19-6$ (Hu19)	[2,25]
3.661	2731.0	[Al VI]	$^3P_1-^3P_2$	[8-10]
3.69263	2708.10	H I	$n=18-6$ (Hu18)	[2,25]
3.7240	2685.3	H <sub>2</sub>	$v=0-0$ S(14)	[26]
3.74056	2673.40	H I	$n=8-5$ (Pfy)	[2]
3.80741	2626.46	H <sub>2</sub>	$v=1-0$ O(7)	[14,27]
3.8462	2600.0	H <sub>2</sub>	$v=0-0$ S(13)	[26,27]
3.935	2541	[Si IX]	$^3P_1-^3P_0$	[9,10,15]
3.95300	2529.72	H <sub>3</sub> <sup>+</sup>	$v=\nu_2(1)-0; (1,0,-1)-(1,0)$	[28]
4.0045	2497.2	SiO	$v=2-0$ band head	[29]
4.02087	2487.02	H I	$n=14-6$ (Hu14)	[2,16]
4.03781	2476.59	He I	$5f\ ^3F^o-4d\ ^3D$	[3,30]
4.04900	2469.75	He I	$5g\ ^1G-4f\ ^1F^o; 5g\ ^3G-4f\ ^3F^o$	[30]
4.05226	2467.76	H I	$n=5-4$ (Br $\alpha$ )	[2,16]
4.17079	2397.63	H I	$n=13-6$	[2,16]
4.64931	2150.86	CO	$v=1-0$ R(1)	[31]
4.65378	2148.79	H I	$n=7-5$ (Pfb)	[2,16]
4.65748	2147.08	CO	$v=1-0$ R(0)	[31]
4.67415	2139.43	CO	$v=1-0$ P(1)	[31]
4.68262	2135.55	CO	$v=1-0$ P(2)	[31]
4.69462	2130.10	H <sub>2</sub>	$v=0-0$ S(9)	[14]
5.0531	1979.0	H <sub>2</sub>	$v=0-0$ S(8)	[14,26]
6.634	1507	[Ni II]	$a\ ^2D_{3/2}-a\ ^2D_{5/2}$	[32]
6.985	1432	[Ar II]	$^2P_{1/2}^o-^2P_{3/2}^o$	[33]
7.642	1309	[Ne VI]	$^2P_{3/2}-^2P_{1/2}$	[9,10]
8.99135	1112.18	[Ar III]	$^3P_1-^3P_2$	[33,34]
10.51	951.5	[S IV]	$^2P_{3/2}^o-^2P_{1/2}^o$	[33]
10.521	950.48	[Co II]	$a\ ^3F_3-a\ ^3F_4$	[11,32]
12.2786	814.425	H <sub>2</sub>	$v=0-0$ S(2)	[14]
12.3720	808.283	H I	$n=7-6$ (Hu $\alpha$ )	[2]
12.8135	780.424	[Ne II]	$^2P_{1/2}^o-^2P_{3/2}^o$	[33,34]
15.56	642.7	[Ne III]	$^3P_1-^3P_2$	[33]
17.0348	587.032	H <sub>2</sub>	$v=0-0$ S(1)	[14]
18.7130	534.387	[S III]	$^3P_2-^3P_1$	[34,35]
24.3158	411.256	[Ne V]	$^3P_1-^3P_0$	[34,35]
25.87	386.5	[O IV]	$^2P_{3/2}-^2P_{1/2}$	[33]
28.2188	354.374	H <sub>2</sub>	$v=0-0$ S(0)	[14]

Table 7.10. *Continued.*

$\lambda$ ( $\mu\text{m}$ ) <sup>a</sup>	$\nu$ ( $\text{cm}^{-1}$ ) <sup>a</sup>	Species	Transition <sup>b</sup>	Reference <sup>c</sup>
33.482	298.67	[S III]	$^3P_1-^3P_0$	[35,36]
51.816	192.99	[O III]	$^3P_2-^3P_1$	[33,35]
57.317	174.47	[N III]	$^2P_{3/2}^o-^2P_{1/2}^o$	[33]
63.1837	158.269	[O I]	$^3P_1-^3P_2$	[37]
77.059	129.77	CO	$J=34-33$	[37]
88.355	113.18	[O III]	$^3P_1-^3P_0$	[33,35]
119.23	83.872	OH	$^2\Pi_{3/2} J=5/2-3/2$	[37]
119.44	83.724	OH	$^2\Pi_{3/2} J=5/2-3/2$	[37]
121.898	82.0358	[N II]	$^3P_2-^3P_1$	[33,38]
124.65	80.225	NH <sub>3</sub>	$K=3, J=4-3, a-s$	[37]
145.526	68.7162	[O I]	$^3P_0-^3P_1$	[33]
157.741	63.3951	[C II]	$^2P_{3/2}^o-^2P_{1/2}^o$	[33]
162.81	61.421	CO	$J=16-15$	[37]
205.178	48.7382	[N II]	$^3P_1-^3P_0$	[38]
370.415	26.9967	[C I]	$^3P_2-^3P_1$	[33]
371.65	26.907	CO	$J=7-6$	[39]
609.135	16.4167	[C I]	$^3P_1-^3P_0$	[33]

## Notes

<sup>a</sup>Vacuum wavelengths and frequencies are given.

<sup>b</sup>Transition shown is (upper level)-(lower level).

<sup>c</sup>Because of space limitations, only a few transitions of each species are shown; see references for additional lines. Wavelength and frequencies were calculated or obtained from primary references where possible. For additional information, see [40-45].

## References

1. Treffers, R.R., *et al.* 1976, ApJ, **209**, 793
2. Moore, C.E. 1993, in Tables of Spectra of Hydrogen, Carbon, Nitrogen, and Oxygen Atoms and Ions, ed. J. W. Gallagher (CRC, Boca Raton, FL); van Hoof, P.A.M., private communication
3. Bashkin, S., & Stoner, J.O. 1975, Atomic Energy Levels and Grotian Diagrams (North-Holland, Amsterdam); van Hoof, P.A.M., private communication
4. Allen, D.A., *et al.* 1985, ApJ, **291**, 280
5. Johansson, S. 1978, Phys. Scr., **18**, 217
6. Hamann, F., *et al.* 1994, ApJ, **422**, 626
7. Moore, C.E. 1971, Atomic Energy Levels, NSRDS-NBS Publication No. 35; van Hoof, P.A.M., private communication
8. Woodward, C.E., *et al.* 1995, ApJ, **438**, 921
9. Greenhouse, M.A., *et al.* 1993, ApJS, **88**, 23
10. Gehrz, R.D. 1988, ARA&A, **26**, 377
11. Roche, P.F., *et al.* 1993, MNRAS, **261**, 522
12. Hinkle, K.H. 1978, ApJ, **220**, 210
13. Gautier III, T.H., *et al.* 1976, ApJ, **207**, L129
14. Black, J.H., & van Dishoeck, E.F. 1987, ApJ, **322**, 412
15. Reconditi, M., & Oliva, E. 1993, A&A, **274**, 662; Oliva, E., *et al.* 1994, A&A, **288**, 457
16. Scoville, N., *et al.* 1983, ApJ, **275**, 201
17. Drossart, P., *et al.* 1989, Nature, **340**, 539; see also Kao, L., *et al.* 1991, ApJS, **77**, 317
18. Simon, M., & Cassar, L. 1984, ApJ, **283**, 179
19. Kleinman, S.G., & Hall, D.N.B. 1986, ApJS, **62**, 501
20. Martin, W.C., & Zalubas, R. 1981, J. Phys. Chem. Ref. Data Ser., **10**, 153
21. Black, J.H., & Willner, S.P. 1984, ApJ, **279**, 673
22. Davis, D.S., *et al.* 1982, ApJ, **259**, 166
23. Beer, R., *et al.* 1972, ApJ, **172**, 89



24. Lowe, R.P., *et al.* 1991, ApJ, **368**, 195
25. Sanford, S.A. 1991, ApJ, **376**, 599
26. Knacke, R.F., & Young, E.T. 1981, ApJ, **249**, L65
27. Brand, P.W.J.L., *et al.* 1989, MNRAS, **236**, 929
28. Oka, T., & Geballe, T.R. 1990, ApJ, **351**, L53
29. Hinkle, K.H., *et al.* 1976, ApJ, **210**, L141
30. Hamann, F., & Simon, M. 1986, ApJ, **311**, 909
31. Guelachvili, G. 1979, J. Mol. Spectrosc., **75**, 251; Mitchell, G.F., *et al.* 1989, ApJ, **341**, 1020
32. Wooden, D.H., *et al.* 1993, ApJS, **88**, 477
33. Genzel, R. 1988, in Millimetre and Submillimetre Astronomy, ed. R. D. Wolstencroft & W. B. Burton (Kluwer, Dordrecht), p. 223
34. Kelly, D.M., & Lacy, J.H. 1995, ApJ, **454**, L161
35. Emery, R.J., & Kessler, M.F. 1984, in Galactic and Extragalactic Infrared Spectroscopy, ed. M. F. Kessler and J. P. Phillips (Reidel, Dordrecht), p. 289
36. Stacy, G.J., *et al.* 1993, Proc. SPIE, **1946**, 238
37. Watson, D.M. 1984, in Galactic and Extragalactic Infrared Spectroscopy, ed. M. F. Kessler & J. P. Phillips (Reidel, Dordrecht), p. 195; Townes, C.H., & Melnick, G. 1990, PASP, **102**, 357
38. Colgan, S.W.J., *et al.* 1993, ApJ, **413**, 237
39. Howe, J.E., *et al.* 1993, ApJ, **410**, 179
40. H. Wynn-Williams, C.G. 1984, in Galactic and Extragalactic Infrared Spectroscopy, ed. M. F. Kessler and J. P. Phillips (Reidel, Dordrecht), p. 133
41. H<sub>2</sub>: Schwartz, R.D., *et al.* 1987, ApJ, **322**, 403; Black, J.H., & van Dishoeck, E.F. 1987, ApJ, **322**, 412
42. CO: Goorvitch, D. 1994, ApJS, **95**, 535
43. Solar atlases: Livingston, W., & Wallace, L. 1991, An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm<sup>-1</sup> (1.1–5.4 μm), NSO Technical Report No. 91-001 (NOAO, Tucson); Wallace, L., & Livingston, W. 1992, An Atlas of a Dark Sunspot Umbral Spectrum from 1970 to 8640 cm<sup>-1</sup> (1.16–5.1 μm), NSO Technical Report No. 92-001 (NOAO, Tucson)
44. Infrared spectra: Jourdain de Muizon, M., *et al.* 1994, Database of Astronomical Infrared Spectroscopic Observations (University of Leiden, Leiden)
45. Infrared wavelength calibration: Outred, M. 1978, J. Phys. Chem. Ref. Data Ser., **7**, 1; Rao, K.N., *et al.* 1966, Wavelength Standards in the Infrared (Academic, New York)

## 7.8 DUST

For the infrared interstellar reddening law, see [66–69].

The total to selective absorption ( [66–68], for  $R = A_V/E(B - V) = 3.1$ ) is

$$A_V/E(J - K) = 5.82 \pm 0.1, \quad A_V/E(H - K) = 15.3 \pm 0.6,$$

$$A_V/E(V - K) = 1.13 \pm 0.03,$$

$$A_\lambda/E(J - K) = 2.4(\lambda)^{-1.75} \quad (\text{for } 0.9 < \lambda < 6 \mu\text{m}).$$

The color excess ratio [67] is

$$E(J - H)/E(H - K) = 1.70 \pm 0.05.$$

The ratio of visual extinction to silicate band optical depth ( $\tau_{\text{si}}$ ) [68, 70, 71] is

$$A_V/\tau_{\text{si}} = 19 \pm 1 \quad (\text{local interstellar medium}),$$

$$A_V/\tau_{\text{si}} = 11 \pm 2 \quad (\text{Galactic Center region}).$$

The average visual extinction to the Galactic Center region is 34 mag. [72] and to individual sources it ranges from 23 to 35 mag. [67].

The extinction cross section per H nucleus in the local interstellar medium [68] is

$$N_{\text{H}}/E(J - K) = 1.1 \times 10^{22} \text{ nuclei cm}^{-2} \text{ mag.}^{-1}.$$

The interstellar linear polarization [73–75]:

$$P(\lambda)/P_{\text{max}} = \exp[-K \ln^2(\lambda_{\text{max}}/\lambda)] \quad (\text{for } \lambda < 2 \mu\text{m}),$$

$$P(\lambda) \propto \lambda^{-\beta}, \quad \beta = 1.6 - 2.0 \quad (\text{for } 2 < \lambda < 5 \mu\text{m}),$$

where  $P(\lambda)$  is the percentage polarization,  $P_{\text{max}}$  is the maximum percentage polarization occurring at  $\lambda_{\text{max}}$ , and  $K = 0.01 \pm 0.05 + (1.66 \pm 0.09)\lambda_{\text{max}}$ .

Table 7.11 and Figure 7.5 present data on the interstellar dust emission. Table 7.12 presents far-infrared dust properties.

**Table 7.11.** Average galactic diffuse emission<sup>a</sup> [1].

$\lambda$ ( $\mu\text{m}$ )	$\nu I_\nu$ ( $10^{-7} \text{ W m}^{-2} \text{ sr}^{-1}$ )	$\lambda$ ( $\mu\text{m}$ )	$\nu I_\nu$ ( $10^{-7} \text{ W m}^{-2} \text{ sr}^{-1}$ )
3.5	0.21	60	0.88
4.9	0.13	100	2.0
12	0.80	140	3.8
25	0.41	240	2.5

**Note**

<sup>a</sup>For galactic latitudes  $-6^\circ$  to  $-4^\circ$  and  $+4^\circ$  to  $+6^\circ$ . Emission is highly variable on small spatial scales [1,2].

**References**

1. Bernard, J.P., *et al.* 1994, A&A, **291**, L5
2. Cutri, R.M., & Latter, W.B., eds. 1993, The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds, ASP Conf. Ser. (ASP, San Francisco), Vol. 58

The dust mass estimate from the 100- $\mu\text{m}$  flux density is

$$M_{\text{dust}} = 4.81 \times 10^{-12} f_{100} D^2 (e^{143.88/T_d} - 1) M_\odot,$$

where  $f_{100}$  is the 100- $\mu\text{m}$  flux density in Jy,  $D$  is the distance in pc, and  $T_d$  is the dust temperature in K. The derivation follows from [76], using a mass absorption coefficient of  $2.5 \text{ m}^2 \text{ kg}^{-1}$  at 100  $\mu\text{m}$ . The dust mass absorption coefficient at submillimeter wavelengths is estimated in [68, 76, 77].

The equilibrium dust temperature of a particle with albedo  $A$  at a distance  $r$  (in pc) from a source of luminosity  $L$  (in  $L_\odot$ ) is

$$T_e = 0.612(1 - A)^{0.25} L^{0.25} r^{-0.5} \text{ K}.$$

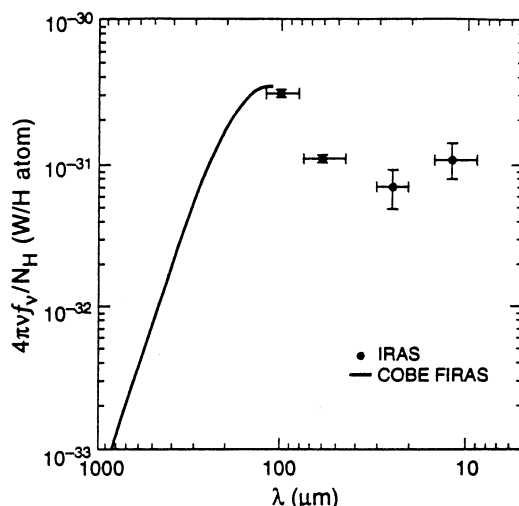


Figure 7.5. Emission spectrum of interstellar dust. Adapted from [78]. See also [26, 79, 80].

The nonequilibrium emission from extremely small particles is discussed in [81–83].

**Table 7.12.** Galactic dust properties at 140–240  $\mu\text{m}$ . Mean values in the Galactic plane ( $|b| < 1^\circ$ )<sup>a</sup>. [1]

Quantity	Inner Galaxy ( $270^\circ < \ell < 350^\circ$ ; $10^\circ < b < 90^\circ$ )	Outer Galaxy ( $90^\circ < \ell < 270^\circ$ )	Entire Galaxy
Dust temperature (K)	$20 \pm 1$	$17 \pm 1$	$19 \pm 1$
240 $\mu\text{m}$ optical depth	$(5.0 \pm 2.0) \times 10^{-3}$	$(9.5 \pm 3.0) \times 10^{-4}$	$(3.0 \pm 1.0) \times 10^{-3}$
Total FIR radiance ( $\text{W m}^{-2} \text{sr}^{-1}$ )	$(3.7 \pm 0.3) \times 10^{-5}$	$(2.4 \pm 0.2) \times 10^{-6}$	$(2.0 \pm 0.2) \times 10^{-5}$
Gas-to-dust ratio	$140 \pm 50$	$190 \pm 60$	$160 \pm 60$
FIR luminosity per H mass ( $L_\odot/M_\odot$ )	$3.0 \pm 0.3$	$0.9 \pm 0.1$	$2.0 \pm 0.2$

**Note**

<sup>a</sup>Data from the Cosmic Background Explorer (COBE) satellite; for additional information see the COBE WWW Home Page: [http://www.gsfc.nasa.gov/astro/cobe/cobe\\_home.html](http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html)

**Reference**

1. Sodroski, T.J., *et al.* 1994, *ApJ*, **428**, 638

Spectral features of dust and ice in the infrared are listed in Table 7.13.

**Table 7.13.** Major dust and ice features [1–7].

$\lambda$ ( $\mu\text{m}$ )	Identification	Where observed
3.08	H <sub>2</sub> O ice	Molecular clouds; OH-IR stars
3.29, 6.2, 7.7,	Aromatic hydrocarbons <sup>a</sup>	H II regions, planetary nebulae, reflection nebulae,

Table 7.13. *Continued.*

$\lambda$ ( $\mu\text{m}$ )	Identification	Where observed
8.65, 11.25		young and evolved stars, starburst galaxies
4.62	“X-CN”	Molecular clouds
4.67	CO ice	Molecular clouds
6.0	H <sub>2</sub> O ice	Molecular clouds
6.85	CH <sub>3</sub> OH + other	Molecular clouds
~9.7	Amorphous silicates	H II regions, molecular clouds
~11.2	SiC	Circumstellar shells; planetary nebulae
11.5	H <sub>2</sub> O ice	OH-IR stars
~18	Amorphous silicates	H II regions; Galactic Center
~34	MgS (?)	Planetary nebulae; carbon stars
43	H <sub>2</sub> O ice	OH-IR stars

**Note**

<sup>a</sup>The nature of the “aromatic hydrocarbons” is not known precisely [7]; it is commonly assumed to be polycyclic aromatic hydrocarbons (PAHs).

**References**

1. Willner, S.P. 1984, in *Galactic and Extragalactic Infrared Spectroscopy*, ed. M. F. Kessler and J. P. Phillips (Reidel, Dordrecht), p. 37
2. Roche, P.F. 1989, in *Proc. 22nd ESLAB Symp. on Infrared Spectroscopy in Astronomy*, ESA SP-290, p. 79
3. Tokunaga, A.T. & Brooke, T.Y. 1990, *Icarus*, **86**, 208
4. Whittet, D.C.B. 1992, *Dust in the Galactic Environment* (Institute of Physics, Bristol), p. 147
5. Allamandola, L.J. *et al.*, 1989, *ApJS*, **71**, 733
6. Léger, A. & d’Hendecourt, L. 1987, in *Polycyclic Aromatic Hydrocarbons and Astrophysics*, ed. A. Léger *et al.* (Reidel, Dordrecht), p. 223
7. Sellgren, K. 1994, in *The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds*, ed. R.M. Cutri & W. B. Latter, ASP Conf. Ser. (ASP, San Francisco), Vol. 58, p. 243

**7.9 SOLAR SYSTEM**

The solar colors are [84]

$$J - H = 0.310, \quad H - K = 0.060, \quad K - L = 0.034, \quad L - M = -0.053, \quad V - K = 1.486.$$

Solar analogs [85] are 16 Cyg B, VB64, HD 105590, HR 2290.

The blackbody temperature of an object without an atmosphere in the solar system is

$$T_b = 278.8(1 - A)^{0.25} r^{-0.5} \text{ K},$$

where  $A$  is the albedo and  $r$  is the distance from the Sun in A.U.

For thermal emission from asteroids, see [86–88].

For the infrared spectra of planetary atmospheres, see [89–92].

For the infrared spectra of comets, see [93, 94].

For near-infrared spectra of satellites, see [95, 96].

For near-infrared spectra of asteroids, see [97, 98].

The infrared magnitudes and colors of many solar system objects are given in Table 7.14.

**Table 7.14.** *Magnitudes of selected solar system bodies.*<sup>a</sup>

Object	Ref.	$V(1,0)^b$	$\Delta V^c$	$V - J$	$J - H$	$H - K$	$K - L$	$V - N$	$V - Q$	$T$ (K) <sup>d</sup>
J1 Io	[1-4]	-1.68	0.15	1.3	0.35	0.08	0.00	4.70	9.29	137 <sup>e</sup>
J2 Europa (L)	[1-5]	-1.37	0.3	1.2	-0.31	-0.35	-2.24	3.91	8.81	130 <sup>e</sup>
J2 Europa (T)	[1-5]			1.4	-0.37	-0.53	-2.35			
J3 Ganymede (L)	[1-5]	-2.08	0.15	1.0	-0.10	-0.08	-1.90	5.69	10.26	142 <sup>e</sup>
J3 Ganymede (T)	[1-5]				-0.07	-0.07	-1.44			
J4 Callisto	[1-5]	-0.95	0.13	1.5	-0.27	0.07	-1.01	7.26	11.72	152 <sup>e</sup>
S2 Enceladus	[6-8]	1.9	0.5	1.06	-0.05	-0.24	< -0.5			
S3 Tethys	[4,6,7]	0.7	0.1	0.9	-0.20	-0.16				
S4 Dione	[4,6,7]	0.88	0.3	0.8	-0.20	-0.12				
S5 Rhea	[4,5,8,9]	0.1	0.2	1.06	-0.05	-0.24	-1.6		8.5	
S6 Titan	[4,10-13]	-1.3	0.0	0.2	-0.31	-0.38	-1.7	6.3		76 <sup>f</sup>
S8 Iapetus (L)	[13-15]	2.4		1.60	0.4	0.05				
S8 Iapetus (T)	[13-15]	0.6		0.8	-0.11	-0.13				
U1 Ariel	[4,16]	1.7		1.20	0.21	-0.04				
U2 Umbriel	[7,9]	2.4		1.30	0.25	-0.09			10.4	
U3 Titania	[4,7,9]	1.3		1.30	0.20	-0.14			10.0	
U4 Oberon	[7,9]	1.6		1.35	0.20	-0.14			10.4	
N1 Triton	[5,8,17,18]	-1.0		1.3	0.31	-0.24			>8.2	38 <sup>d</sup>
Pluto,Charon	[17,19-21]	-0.76	0.30	1.3	-0.01	-0.36			>9.9	55 <sup>g</sup>
1 Ceres	[22-28]	3.72	0.04	1.2	0.31	0.05		10.0	12.8	245 <sup>h</sup>
2 Pallas	[22-28]	4.45	0.16	1.2	0.21	0.04		9.9	12.4	270 <sup>h</sup>
3 Juno	[22-28]	5.73	0.22			0.05		8.7	12.0	230 <sup>h</sup>
4 Vesta	[22-28]	3.55	0.12	1.4	0.17	0.01		8.4	11.2	250 <sup>h</sup>

#### Notes

<sup>a</sup>Average magnitude given unless indicated otherwise; (L)=leading hemisphere, (T)=trailing hemisphere. Approximate filter wavelengths: V(0.55  $\mu\text{m}$ ), J(1.25  $\mu\text{m}$ ), H(1.65  $\mu\text{m}$ ), K(2.2  $\mu\text{m}$ ), L(3.45  $\mu\text{m}$ ), N(10  $\mu\text{m}$ ), Q(20  $\mu\text{m}$ ); see references for details.

<sup>b</sup> $V(1,0)$ = absolute visual magnitude at a distance of 1 A.U. from the Earth and 1 A.U. from the Sun at 0° phase angle. The apparent visual magnitude of an object is  $V(r, \Delta, \alpha) = V(1,0) + C\alpha + 5 \log(r\Delta)$ , where  $r$  is the heliocentric distance and  $\Delta$  is the geocentric distance (both in A.U.),  $C$  is the phase coefficient in  $\text{mag deg}^{-1}$ , and  $\alpha$  is the phase angle (deg). The opposition effect, occurring when  $\alpha \approx 0^\circ$ , is not included in this table.

<sup>c</sup> $\Delta V$ =visual light curve amplitude (peak to peak).

<sup>d</sup> $T_B$  = brightness temperature;  $T_S$  = surface or subsolar temperature.

<sup>e</sup> $T_B(10 \mu\text{m})$

<sup>f</sup> $T_B(100 \mu\text{m})$

<sup>g</sup> $T_B(60 \mu\text{m})$

<sup>h</sup> $T_S(10 \mu\text{m})$

#### References

- Morrison, D., *et al.* 1976, ApJ, **207**, L213
- Morrison, D. 1977, in Planetary Satellites, ed. J. A. Burns (University of Arizona, Tucson), p. 269
- Morrison, D., & Morrison, N.D. 1977, in Planetary Satellites, ed. J. A. Burns (University of Arizona, Tucson), p. 363
- Morrison, D., & Cruikshank, D.P. 1974, SSRv, **15**, 641
- Hartmann, W.K., *et al.* 1982, Icarus, **52**, 377
- Franz, O.G., & Millis, R.L. 1975, Icarus, **24**, 433
- Cruikshank, D.P. 1980, Icarus, **41**, 246, and private communication
- Cruikshank, D.P., *et al.* 1977, ApJ, **217**, 1006
- Brown, R.H., *et al.* 1982, Nature, **300**, 423
- Andersson, L.E. 1977, in Planetary Satellites, ed. J. A. Burns, (University of Arizona, Tucson), p. 451

11. Noll, K.S., & Knacke, R.F. 1993, *Icarus*, **101**, 272
12. Gillett, F.C. 1975, *ApJ*, **201**, L41
13. Loewenstein, R.F., *et al.* 1980, *Icarus*, **43**, 283
14. Cruikshank, D.P., *et al.* 1983, *Icarus*, **53**, 90
15. Cruikshank, D.P., *et al.* 1979, *Rev. Geophys. Space Phys.*, **17**, 165
16. Nicholson, P.D., & Jones, T.J. 1980, *Icarus*, **42**, 54
17. Morrison, D., *et al.* 1982, *Nature*, **300**, 425
18. Tryka, K.A., *et al.* 1993, *Science*, **261**, 751
19. Binzel, R.P., & Mulholland, J.D. 1984, *AJ*, **89**, 1759
20. Soifer, B.T., *et al.* 1980, *AJ*, **85**, 166
21. Jewitt, D.C. 1994, *AJ*, **107**, 372
22. Veeder, G.J., *et al.* 1978, *AJ*, **83**, 651, and private communication
23. Lagerkvist, C.-L., *et al.* 1989, in *Asteroids II*, ed. R. P. Binzel, *et al.* (University of Arizona, Tucson), p. 1162
24. Tedesco, E. 1979, in *Asteroids*, ed. T. Gehrels (University of Arizona, Tucson), p. 1098
25. Johnson, T.V., *et al.* 1975, *ApJ*, **197**, 527
26. Morrison, D. 1974, *ApJ*, **194**, 203
27. Lebofsky, L.A., *et al.* 1986, *Icarus*, **68**, 239
28. McCheyne, R.S., *et al.* 1985, *Icarus*, **61**, 443

## 7.10 STARS

Molecular features seen in cool stars are listed in Table 7.15.

**Table 7.15.** *Molecular bands in cool stars [1,2].*

Molecule	Bands	Wavelength range ( $\mu\text{m}$ )	Selected references
CO	$\Delta\nu = 1,2,3$	1.5–4.7	[3,4,5,6,7,8,9]
H <sub>2</sub>	$\Delta\nu = 1$ (quadrupole vib-rot)	1.7–2.5	[3]
H <sub>2</sub> O	$\nu_3, 2\nu_2, \nu_2 + \nu_3 - \nu_2,$ $\nu_2 + \nu_3, \nu_1 + \nu_2$	1.3–3.6	[10,11]
CN	$A^2\Pi-X^2\Sigma^+$	<4	[3,4,6,12,13,14,15]
C <sub>2</sub>	$b^1\Pi_u-x^1\Sigma_g^+$ (Phillips) $A'^3\Sigma_g^- - X'^3\Pi_u$ (Ballik-Ramsey)	<2.5	[3,6,14,16]
C <sub>3</sub> , C <sub>5</sub>	$\nu_3$	4–5	[12,17,18]
HCN	$\nu_2, \nu_3, 2\nu_2, 3\nu_2, 2\nu_1 + \nu_2$	2–5, 7.1, 14	[13,15,16,19]
C <sub>2</sub> H <sub>2</sub>	$\nu_3, \nu_5, \nu_1 + \nu_5$	2.5–4, 14	[13,16,19]
SiO	$\Delta\nu = 1,2$	4–4.2, 8.0–8.3	[9,20,21,22,23]
OH	$\Delta\nu = 1,2$	1.6–2.0, 3.1–4.0	[8,22,24]
CH	$\Delta\nu = 1$	3.3–4.0	[3,22]
CS	$\Delta\nu = 2$	3.8–4.0	[22,23]

### References

1. Merrill, K.M., & Ridgway, S.T. 1979, *ARA&A*, **17**, 9
2. Tsuji, T. 1986, *ARA&A*, **24**, 89
3. Lambert, D.L., *et al.* 1986, *ApJS*, **62**, 373
4. Thompson, R.I., *et al.* 1972, *PASP*, **84**, 779
5. Ridgway, S.T., *et al.* 1974, in *Highlights of Astronomy*, ed. G. Contopoulos (Reidel, Dordrecht), Vol. 3, p. 327
6. Querci, M., & Querci, F. 1975, *A&A*, **42**, 329
7. Geballe, T.R., *et al.* 1977, *PASP*, **89**, 840
8. Hinkle, K.H. 1978, *ApJ*, **220**, 210
9. Cohen, M., *et al.* 1992, *AJ*, **104**, 2045
10. Strecker, D.W., *et al.* 1978, *AJ*, **83**, 26
11. Hinkle, K.H., & Barnes, T.G. 1979, *ApJ*, **227**, 923

12. Goebel, J.H., *et al.* 1978, ApJ, **222**, L129
13. Goebel, J.H., *et al.* 1981, ApJ, **246**, 455
14. Goebel, J.H., *et al.* 1983, ApJ, **270**, 190
15. Wiedemann, G.R., *et al.* 1991, ApJ, **282**, 321
16. Goebel, J.H., *et al.* 1980, ApJ, **235**, 104
17. Hinkle, K.H., *et al.* 1988, Science, **241**, 1319
18. Bernath, P.F., *et al.* 1989, Science, **244**, 562
19. Ridgway, S.T., *et al.* 1978, ApJ, **255**, 138
20. Geballe, T.R., *et al.* 1979, ApJ, **230**, L47
21. Rinsland, C.P., & Wing, R.F. 1982, ApJ, **262**, 201
22. Ridgway, S.T., *et al.* 1984, ApJS, **54**, 177
23. Lambert, D.L., *et al.* 1990, AJ, **99**, 1612
24. Beer, R., *et al.* 1972, ApJ, **172**, 89

For the spectrophotometry of standard stars, see [99–102].

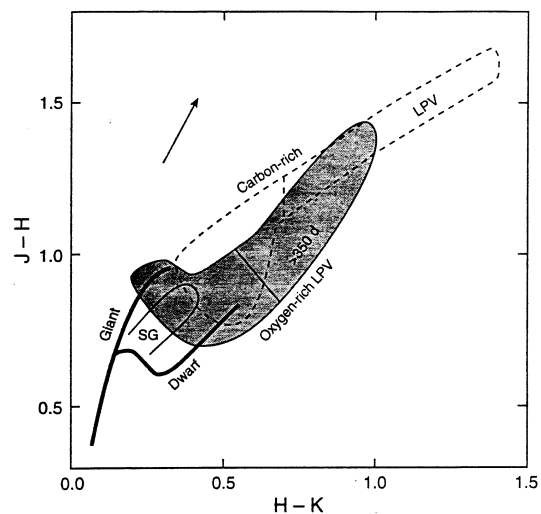
For the infrared star count models, see [103–105].

Useful catalogs are found in [106–109].

For near-infrared spectra of young stars, see [110–118].

For spectral energy distributions of young stellar objects and pre-main sequence stars, see [119–124].

Figure 7.6 shows the color-color diagram for stars.



**Figure 7.6.** Color-color diagram for various classes of stars, adapted from [17]. The dark line indicates the location of G5 to M6 main sequence dwarf and giant stars. The dashed lines indicate the boundary for most carbon-rich stars; the carbon long-period variable (LPV) stars lie to the right. The oxygen-rich (M type) LPV stars fall within the boundary of the solid line, and the LPV stars with periods greater than 350 days are to the right and overlap the carbon-rich LPV stars. The supergiant M stars (SG) lie in a region below and to the right of the giant sequence. The arrow indicates the direction of the interstellar reddening.

## 7.11 EXTRAGALACTIC OBJECTS

### 7.11.1 Energy Distributions and Colors

Infrared energy distributions of galaxies vary widely. Representative examples may be found in [125, 126]. At least five different physical causes have been identified for the continuum infrared emission from galaxies:

(A) Photospheric emission from evolved stars (usually dominant in the 1–3- $\mu\text{m}$  region) [127, 128]: Mean colors of elliptical galaxies (CIT photometric system):  $V-K = 3.33$  mag;  $J-H$

= 0.69 mag;  $H-K = 0.21$  mag. Molecular absorption bands in elliptical galaxies  $\text{H}_2\text{O}$  ( $1.95 \mu\text{m}$ ) = 0.12 mag;  $\text{CO}$  ( $2.3 \mu\text{m}$ ) = 0.16 mag. For additional near-infrared colors, see [129–132].

(B) Dust shells around evolved stars [133]: This is the main cause of 10–12- $\mu\text{m}$  emission in elliptical galaxies, for which  $f_\nu(12 \mu\text{m}) = 0.13f_\nu(2.2 \mu\text{m})$ . Units of  $f_\nu$  are Jy.

(C) Emission from interstellar dust [134, 135]: Transiently heated “small” grains dominate at about 10  $\mu\text{m}$ ; “large” grains in thermal equilibrium dominate at 50–100  $\mu\text{m}$ . A typical energy distribution from dust emission in a starburst galaxy normalized to 60  $\mu\text{m}$  is  $f_\nu(12 \mu\text{m}) = 0.035$ ;  $f_\nu(25 \mu\text{m}) = 0.18$ ;  $f_\nu(60 \mu\text{m}) = 1.0$ ;  $f_\nu(100 \mu\text{m}) = 1.41$  [136].

(D) Seyfert nucleus: Seyfert galaxies exhibit infrared emission from dust heated by the central source, as well as emission from starburst or nonthermal components. Seyfert galaxies tend to be most prominent at 60  $\mu\text{m}$ , but energy distributions vary widely. The IRAS 25–60- $\mu\text{m}$  spectral slope has been found useful for selecting Seyfert galaxies [137, 138].

(E) Blazar component: Nonthermal, approximately power-law emission ( $f_\nu \propto \nu^\alpha$ ). Mean values are  $\alpha(1 \mu\text{m}) = -1.42 \pm 0.95$ ;  $\alpha(10 \mu\text{m}) = -1.12 \pm 0.47$ ;  $\alpha(100 \mu\text{m}) = -0.88 \pm 0.43$ ;  $\alpha(1 \text{mm}) = -0.18 \pm 0.42$  [139].

For far-infrared colors of extragalactic objects, see [125, 140–143]

### 7.11.2 Statistics of Galaxies at Infrared Wavelengths

*Galaxy number counts at 2.2  $\mu\text{m}$ .* The number of galaxies per square degree per magnitude is [144]:

$$dN/dK = 4000 \times 10^{\alpha(K-17)},$$

where  $\alpha = 0.67$  for  $10 < K < 17$ ,  $\alpha = 0.26$  for  $17 < K < 23$ , and  $K = 2.2 \mu\text{m mag}$ .

*Luminosity function at 60  $\mu\text{m}$*  [125, 145]. The density of galaxies per cubic megaparsec per magnitude interval at 60  $\mu\text{m}$  is

$$\log(\rho) = -3.2 - \alpha \{ \log[\nu L_\nu(60 \mu\text{m})] - 10.2 \},$$

where  $\nu L_\nu(60 \mu\text{m})$  is given in units of  $L_\odot$ , and  $\alpha = 0.8$  for  $\log[\nu L_\nu(60 \mu\text{m})] < 10.2$  and  $\alpha = 2.0$  for  $\log[\nu L_\nu(60 \mu\text{m})] > 10.2$ .  $H_0$  is assumed to be  $75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ .

The total infrared energy output of the local universe from 8 to 1000  $\mu\text{m}$  is  $1.24 \times 10^8 L_\odot \text{ Mpc}^{-3}$  [146].

## ACKNOWLEDGMENTS

Many people have helped with their comments and suggestions. I thank in particular the following persons for valuable comments and contributions to this chapter: E. Becklin, M. Cohen, D. Cruikshank, M. Hanner, T. Herter, J. Hora, E. Hu, T. Geballe, I. Glass, R. Knacke, S. Leggett, P. Léna, C. Lonsdale, S. Lord, J. Mazzarella, J. Pipher, S. Ridgway, K. Robertson, P. Roche, K. Sellgren, M. Simon, G. Veeder, M. Werner, G. Wynn-Williams, W. Vacca, and D. Van Buren.

## REFERENCES

1. Lord, S. 1992, NASA Tech. Mem. 103957
2. Manduca, A., & Bell, R.A. 1979, PASP, **91**, 858
3. Bersanelli, M., *et al.* 1991, A&A, **252**, 854



4. Wolfe, W.L., & Zissis, G.J. 1985, *The Infrared Handbook*, revised ed. (U.S. Government Printing Office, Washington, D.C.), p. 5-1
5. Griffin, M.J., *et al.* 1986, *Icarus*, **65**, 244
6. Traub, W.A., & Stier, M.T. 1976, *Appl. Opt.*, **15**, 364
7. Taylor, D.A., *et al.* 1991, *MNRAS*, **251**, 199
8. Taylor, D.A., *et al.* 1994, *Proc. SPIE*, **2198**, 703
9. Melnick, G.J. 1993, *Adv. Space Res.*, **13**, 535
10. Bally, J. 1989, in *Astrophysics in Antarctica*, AIP Conf. No. 198 (AIP, New York), p. 100; Townes, C.H., & Melnick, G. 1990, *PASP*, **102**, 357
11. Buhl, D. 1984, in *Galactic and Extragalactic Infrared Spectroscopy*, ed. M. F. Kessler and J. P. Phillips (Reidel, Dordrecht), p. 221
12. Warner, J.W. 1977, *PASP*, **89**, 724
13. Beckers, J.M. 1979, *PASP*, **91**, 857
14. Wallace, L. 1984, *PASP*, **96**, 184 & 836
15. Krisciunas, K., *et al.* 1987, *PASP*, **99**, 887
16. Volk, K., *et al.* 1989, in *Lecture Notes in Physics*, Vol. 341, ed. E. F. Milone (Springer, Berlin), p. 15
17. Bessell, M.S., & Brett, J.M. 1988, *PASP*, **100**, 1134
18. Hodapp, K.-W., *et al.* 1992, *PASP*, **104**, 441
19. Maihara, T., *et al.* 1993, *PASP*, **105**, 940
20. Shure, M., *et al.* 1994, *Proc. SPIE*, **2198**, 614
21. Becklin, E., private communication
22. Roche, P.F., & Glaspey, A.C.H. 1990, *United Kingdom Large Telescope Report*
23. Binzel, R.P., *et al.*, this volume
24. Hauser, M.G., *et al.* 1984, *ApJ*, **278**, L15
25. Sodroski, T.J., *et al.* 1994, *ApJ*, **428**, 638
26. Cox, P., & Mezger, P.G. 1989, *A&A Rev.*, **1**, 49
27. Wright, E.L. 1993, *SPIE*, **2019**, 158
28. Mather, J.C., *et al.* 1994, *ApJ*, **420**, 439
29. Baker, D.J., & Romick, G.J. 1976, *Appl. Opt.*, **15**, 1966
30. Oliva, E., & Origlia, L. 1992, *A&A*, **254**, 466
31. Steed, A.J., & Baker, D.J. 1979, *Appl. Opt.*, **18**, 3386
32. McCaughrean, M.J. 1988, Ph.D. thesis, University of Edinburgh, Edinburgh
33. Ramsay, S.K., *et al.* 1992, *MNRAS*, **259**, 751
34. Osterbrock, D.E., & Martel, A. 1992, *PASP*, **104**, 76
35. Gillett, F.C. 1987, in *Infrared Astronomy with Arrays*, ed. C. G. Wynn-Williams and E. E. Becklin (University of Hawaii, Honolulu), p. 3
36. Merline, W.J., & Howell, S.B. 1995, *Exp. Astron.*, **6**, 163
37. Phillips, T.G. 1988, in *Millimeter and Submillimeter Astronomy*, ed. R. D. Wolstencroft and W. B. Burton (Kluwer, Dordrecht), p. 1
38. Cohen, M., *et al.* 1992, *AJ*, **104**, 1650
39. Hayes, D.S. 1985, in *Calibration of Fundamental Stellar Quantities*, ed. D. S. Hayes, *et al.*, *Proc. IAU Symp. No. 111* (Reidel, Dordrecht), p. 225
40. Blackwell, D.A., *et al.* 1990, *A&A*, **232**, 396; 1991, *ibid.*, **245**, 567; Campins, H., *et al.* 1985, *AJ*, **90**, 896; Mountain, C.M., *et al.* 1985, *A&A*, **151**, 399
41. Rieke, G.H., *et al.* 1985, *AJ*, **90**, 900
42. Allen, D.A., & Cragg, T.A. 1983, *MNRAS*, **203**, 777
43. Elias, J.H., *et al.* 1982, *AJ*, **87**, 1029
44. Bersanelli, M., *et al.* 1991, *A&A*, **252**, 854
45. Bouchet, P., *et al.* 1991, *A&AS*, **91**, 409
46. Tokunaga, A.T. 1984, *AJ*, **89**, 172
47. Caillault, J.-P., & Patterson, J. 1990, *AJ*, **100**, 825
48. Jones, T.J., & Hyland, A.R. 1982, *MNRAS*, **200**, 509
49. Carrasco, L., *et al.* 1991, *PASP*, **103**, 987
50. Carter, B.S. 1990, *MNRAS*, **242**, 1
51. Hanner, M.S., & Tokunaga, A.T. 1991, in *Comets in the Post-Halley Era*, ed. R. L. Newburn, *et al.* (Kluwer, Dordrecht), p. 67
52. Casali, M., & Hawarden, T. 1992, *JCMT-UKIRT Newsletter*, No. 4, p. 33
53. Gehrz, R.D., *et al.* 1987, in *Encyclopedia of Physical Science and Technology*, ed. R. A. Meyers (Academic, Orlando), Vol. 2, p. 53
54. Elias, J., *et al.* 1985, *ApJS*, **57**, 91
55. Koornneef, J. 1983, *A&AS*, **51**, 489

56. Leggett, S.K., *et al.* 1993, IAU Colloq., **136**, 66
57. Wright, E.L. 1976, ApJ, **210**, 250
58. Orton, G.S., *et al.* 1986, Icarus, **67**, 289
59. Ulrich, B.L. 1981, AJ, **86**, 1619
60. Hildebrand, R.H., *et al.* 1985, Icarus, **64**, 64
61. Sandell, G. 1994, MNRAS, **271**, 75
62. Emerson, J.P. 1988, in Formation and Evolution of Low Mass Stars, ed. A. K. Dupree and M. T. V. T. Lago (Kluwer, Dordrecht), Vol. 241, p. 193
63. Helou, G., *et al.* 1988, ApJS, **68**, 151
64. Pérault, M. 1987, Ph.D. thesis, University of Paris, Paris; Lonsdale, C., & Mazzarella, J., private communication
65. Helou, G., *et al.* 1985, ApJ, **298**, L7
66. Mathis, J.S., this volume
67. Rieke, G.H., & Lebofsky, M.J. 1985, ApJ, **288**, 618
68. Draine, B.T. 1989, in Proceedings of the 22nd ESLAB Symposium on Infrared Spectroscopy in Astronomy, ed. B. H. Kaldeich (ESA, Noordwijk), ESA SP-290, p. 93
69. He, L., *et al.* 1995, ApJS, **101**, 335
70. Roche, P.F., & Aitken, D.K. 1984, MNRAS, **208**, 481
71. Roche, P.F., & Aitken, D.K. 1985, MNRAS, **215**, 425
72. Henry, J.P., *et al.* 1984, ApJ, **285**, L27
73. Nagata, T., *et al.* 1994, ApJ, **423**, L113
74. Martin, P.G., *et al.* 1992, ApJ, **392**, 691
75. Whittet, D.C.B., *et al.* 1992, ApJ, **386**, 562
76. Hildebrand, R.H., *et al.* 1983, QJRAS, **24**, 267
77. Beckwith, S.V.W., & Sargent, A.I. 1991, ApJ, **381**, 250
78. Draine, B.T. 1994, in First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds, ASP Conf. Ser. Vol. 58, eds. R. M. Cutri and W. N. Latter (ASP, San Francisco), p. 227
79. Désert, F.X., *et al.* 1990, A&A, **237**, 215
80. Beichman, C.A. 1987, ARA&A, **25**, 521
81. Sellgren, K. 1984, ApJ, **277**, 623
82. Léger, A., & Puget, J.L. 1984, A&A, **137**, L5
83. Draine, B.T., & Anderson, N. 1985, ApJ, **292**, 494
84. Campins, H., *et al.* 1985, AJ, **90**, 896
85. Hardorp, J. 1982, A&A, **105**, 120
86. Lebofsky, L.A., *et al.* 1986, Icarus, **68**, 239
87. Morrison, D. 1974, ApJ, **194**, 203
88. Tedesco, E.F., *et al.* 1992, The IRAS Minor Planet Survey, Phillips Laboratory Report No. PL-TR-92-2049
89. Hanel, R.A., *et al.* 1992, Exploration of the Solar System by Infrared Remote Sensing (Cambridge University Press, Cambridge)
90. Encrenaz, Th., & Bibring, J.P. 1990, The Solar System (Springer, Berlin)
91. Encrenaz, Th. 1992, in Infrared Astronomy with ISO, eds. Th. Encrenaz and M. F. Kessler (Nova Science, Commack), p. 173
92. Larson, H.P. 1980, ARA&A, **18**, 43
93. Crovisier, J. 1992, in Infrared Astronomy with ISO, ed. Th. Encrenaz and M. F. Kessler (Nova Science, Commack), p. 221
94. Mumma, M.J., *et al.* 1993, in Protostars and Planets III, ed. E. H. Levy and J. I. Lunine (University of Arizona, Tucson), p. 1177
95. Clark, R.N., *et al.* 1986, in Satellites, ed. J. A. Burns and M. S. Matthews (University of Arizona, Tucson), p. 437
96. Cruikshank, D.P., & Brown, R.H., in Satellites, ed. J. A. Burns and M. S. Matthews (University of Arizona, Tucson), p. 836
97. Larson, H.P., & Veeder, G.J. 1979, in Asteroids (University of Arizona, Tucson), p. 724
98. Gaffey, M.F., *et al.* 1989, in Asteroids II, ed. R. P. Binzel, *et al.* (University of Arizona, Tucson), p. 98
99. Merrill, K.M., & Stein, W.A. 1976, PASP, **88**, 285
100. Strecker, D.W., *et al.* 1979, ApJS, **41**, 501
101. Cohen, M., *et al.* 1992, AJ, **104**, 2030
102. Walker, R.G., & Cohen, M. 1992, An Atlas of Selected Calibrated Stellar Spectra, NASA Contractor Report No. 177604
103. Wainscoat, R.J., *et al.* 1992, ApJS, **83**, 111
104. Cohen, M. 1993, AJ, **105**, 1860

105. Cohen, M. 1994, *AJ*, **107**, 582
106. Gezari, D.Y., *et al.* 1993, *Catalog of Infrared Observations*, 3rd ed. NASA Reference Publication No. 1294
107. Gezari, D.Y., *et al.* 1993, *Far Infrared Supplement, Catalog of Infrared Observations* ( $\lambda > 4.6 \mu\text{m}$ ), 3rd ed., Rev. 1, NASA Reference Publication No. 1295
108. Jourdain de Muizon, M., *et al.* 1994, *Database of Astronomical Infrared Spectroscopic Observations* (Leiden University, Leiden)
109. Kleinmann, S.G., & Hall, D.N.B. 1986, *ApJS*, **62**, 501
110. Scoville, N.Z., *et al.* 1983, *ApJ*, **275**, 201
111. Simon, M., & Cassar, L. 1984, *ApJ*, **283**, 179
112. Persson, S.E., *et al.* 1984, *ApJ*, **286**, 289
113. Hamann, F., & Simon, M. 1986, *ApJ*, **311**, 909
114. Schwartz, R.D., *et al.* 1987, *ApJ*, **322**, 403
115. Carr, J.S. 1989, *ApJ*, **345**, 522
116. Mitchell, G.F., *et al.* 1990, *ApJ*, **363**, 554
117. Chandler, C.J., *et al.* 1993, *ApJ*, **412**, L71
118. Hamann, F., *et al.* 1994, *ApJ*, **422**, 626
119. Lada, C.J. 1988, in *Formation and Evolution of Low Mass Stars*, eds. A. K. Dupree and M. T. V. T. Lago (Kluwer Academic, Dordrecht), p. 93
120. Shu, F.H., *et al.* 1987, *ARA&A*, **25**, 23
121. Wilking, B.A. 1989, *PASP*, **101**, 229
122. Lada, E.A., *et al.* 1993, in *Protostars and Protoplanets III*, ed. E. H. Levy and J. I. Lunine (University of Arizona, Tucson), p. 245
123. Zinnecker, H., *et al.* 1993, in *Protostars and Protoplanets III*, ed. E. H. Levy and J. I. Lunine (University of Arizona, Tucson), p. 429
124. André, P., & Montmerle, T. 1994, *ApJ*, **420**, 837
125. Soifer, B.T., *et al.* 1987, *ARA&A*, **25**, 187
126. Telesco, C.M. 1988, *ARA&A*, **26**, 343
127. Frogel, J.A., *et al.* 1978, *ApJ*, **220**, 75
128. Aaronson, M., *et al.* 1978, *ApJ*, **220**, 442
129. Glass, I.S. 1984, *MNRAS*, **211**, 461
130. Glass, I.S., & Moorwood, A.F.M. 1985, *MNRAS*, **214**, 429
131. Sanders, D.B., *et al.* 1988, *ApJ*, **325**, 74
132. Carico, D.P., *et al.* 1988, *AJ*, **95**, 356
133. Knapp, G.R., *et al.* 1992, *ApJ*, **399**, 76
134. Désert, F.X., *et al.* 1990, *A&A*, **237**, 215
135. Knapp, G.R. 1995, in *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M. R. Haas, *et al.*, ASP Conf. Ser. No. 73, p. 121
136. Roche, P.F., *et al.* 1991, *MNRAS*, **248**, 606
137. de Grijp, M.H.K., *et al.* 1985, *Nature*, **314**, 240
138. Glass, I.S. 1985, *MNASSA*, **44**, 60
139. Impey, C.D., & Neugebauer, G. 1988, *AJ*, **95**, 307
140. Soifer, B.T., *et al.* 1989, *AJ*, **98**, 766
141. Mazzarella, J.M., *et al.* 1991, *AJ*, **101**, 2034
142. Cohen, M. 1992, *AJ*, **103**, 1734
143. Walker, H.J., *et al.* 1989, *AJ*, **98**, 2163
144. Gardner, J.P., *et al.* 1993, *ApJ*, **415**, L9
145. Soifer, B.T., *et al.* 1987, *ApJ*, **320**, 238
146. Soifer, B.T., & Neugebauer, G. 1991, *AJ*, **101**, 354