Introduction

More and more investigators are being attracted to work in the infrared spectral region. My intention in this book is to introduce the infrared, its peculiarities and its special techniques, to a new audience that may include established astronomers as well as new students. Basic facts and figures are emphasized and I have not tried to cover all current research. The approach usually avoids the historical and the reader is referred instead to recent books and papers. The origins of ideas are always complex and, with something like 10^4 papers published, it is impossible to do justice to every individual in the field.

The first chapter deals with the basic facts of blackbody radiation, which plays a dominant role in infrared astronomy. A short review of atomic and molecular physics follows in order to provide a convenient reminder of the meaning of spectroscopic nomenclature. The second chapter covers the general properties of the Earth's atmosphere and outlines the main infrared surveys that have taken place or will shortly do so. Chapter 3 is devoted to photometry, emphasizing its fundamental aspects and the importance of traceability and calibration. Chapter 4 is an introduction to spectroscopy, treating firstly the stars. Photodissociation regions, which are of great interest in the infrared and millimeter region, are followed by HII regions and some "Rosetta Stone" spectra of representative objects. Chapter 5 is devoted to dust and its central role in star formation. Finally, because an understanding of the technology is important in obtaining reliable results, the last chapter covers the basics of infrared instrumentation.

Each author of a book in the COHRA series has been asked to name some of the milestones that, in his or her view, line the road of discovery in his subject. My personal choice is based on the feeling that progress in infrared astronomy has been directly attributable to technological advances and new types of instruments.

Milestones of infrared astronomy

- Discovery of infrared radiation whilst examining the warming powers of the Sun's rays as dispersed by a prism (Sir William Herschel, 1800).
- The use of PbS detectors, a product of research during World War II, and newly developed interference filters, by H. L. Johnson and collaborators to set up the first useful photometric system (*ca* 1962).
- The development of the gallium-doped germanium bolometer and all-metal experimental dewars by F. J. Low (*ca* 1961), as well as their application to astronomical photometry soon afterwards.
- The Two-Micron Sky Survey by G. Neugebauer and R. B. Leighton which revealed the existence of stellar objects that radiated predominantly in the infrared (*ca* 1965).
- The launch of the IRAS cryogenically cooled infrared satellite (1983), which permitted the first reliable long-wavelength survey unlimited by the Earth's atmosphere.
- The launch of the ISO pointable observatory-style satellite with spectroscopic instrumentation (1995) that has allowed the detailed examination of specific objects.

Present-day progress

At the present moment, new near-infrared surveys reaching to faint magnitudes, such as DENIS and 2MASS, are revealing a wealth of celestial detail, while IRAS and ISO have opened the mid- and far-infrared wavelength regions to systematic investigation and serendipitous discovery, leading to follow-up studies through the whole observable spectrum.

Infrared arrays have increased in size and sophistication to the point where they offer resolutions and quantum efficiencies similar to the best available in the visible spectrum. The new instruments being designed to exploit them will enable the study of objects in great spatial and spectroscopic detail.

New ground-based telescopes with very large collecting areas are being completed at favourable high-altitude sites, leading to hitherto unattainable sensitivities. Advances in active and adaptive optics have opened new possibilities in the studies involving small angular size. The infrared offers particular advantages for this type of work.

The future

The next few years will see many observations which will exploit the obvious advantages of the new instrumentation. A few of the areas awaiting investigation are:

- The study of primeval galaxies and QSOs at high redshifts.
- The life-cycle of dust in the interstellar medium of galaxies and its relation to the presence of heavy elements at early cosmic times.
- The determination of the shape of the Milky Way galaxy, which has remained a difficult problem because of obscuration by interstellar dust in the Galactic Plane.
- The better understanding of stellar distributions and physical processes occurring near the Galactic Centre, also inhibited hitherto by obscuration.
- The study of the boundary zones between HII regions and molecular clouds – the photodissociation regions.
- The discovery of brown dwarfs and planetary candidates, which are too cool to radiate significantly at visible wavelengths.
- Application of infrared photometry to distance indicators: the often unpredictable systematic effects of interstellar reddening being minimal in the infrared.

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If familiarity has led to a disproportionate number of references to my own work, I hope I will be forgiven. Finally, readers who notice errors or who would like to make suggestions for future editions are invited to contact me at isg@saao.ac.za.

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1

Infrared Emission Mechanisms

1.1 Some photometric definitions

1.1.1 *Source-related terms*

1.1.1.1 Luminosity

The total outward flow of radiation from a body is called its *luminosity* L, measured in W. If divided into spectral intervals, this quantity becomes its *monochromatic luminosity* L_ν, measured in units of W Hz^{-1}, or L_λ, measured in units of W μm^{-1}.

1.1.1.2 Intensity

The power emitted from unit area of a source into unit solid angle is called the *intensity* I and it is measured in W sterad^{-1} m^{-2}. The same quantity, when divided into spectral intervals, is called the *specific intensity* I_ν; similarly for I_λ.

1.1.2 *Receiver-related terms*

1.1.2.1 Flux density

The received radiation, F_ν or F_λ per unit of frequency or wavelength, is measured in terms of W m^{-2} Hz^{-1} or W m^{-2} μm^{-1}.[†] This quantity is known as the *monochromatic flux density* or simply the *monochromatic flux* in astronomical parlance.

The monochromatic flux density is also called the *spectral irradiance.*

Some other photometric terms used outside astronomical circles are given by Sterken and Manfroid (1992) in their general book on photometry.

[†] The MKS unit is W m^{-2} m^{-1}.

Table 1.1. *Some useful physical constants and other quantities*

Symbol	Quantity	Value
c	Velocity of light	2.998×10^{8} m s^{-1}
h	Planck's constant	6.626×10^{-34} J s
k	Boltzmann's constant	1.380×10^{-23} J °K^{-1}
e	Electronic charge	1.602×10^{-19} Coulomb
$L_{\odot}$	Solar luminosity	3.83×10^{26} W
$M_{\odot}$	Solar mass	1.989×10^{30} kg
σ	Stefan's constant	5.669×10^{-8} W m^{-2} °K^{-4}
π		3.14159
e	Base of natural logs	2.71828

Flux densities in frequency units can be converted into wavelength units and vice versa. The flux density in unit frequency interval is F_ν. Since

$$\lambda = \frac{c}{\nu}$$

we have

$$\mathrm{d}\lambda = -\frac{c}{\nu^2}\mathrm{d}\nu = -\frac{\lambda^2}{c}\mathrm{d}\nu.$$

If we put $\mathrm{d}\lambda = 1$, $\mathrm{d}\nu$ becomes the frequency interval corresponding to unit wavelength interval and we see that

$$F_\lambda = 2.998 \times 10^{8} F_\nu / \lambda^2$$

if λ is expressed in metres and the other quantities are in MKS units.

It is also interesting to note that

$$\nu F_\nu = \lambda F_\lambda$$

if λ is again expressed in metres. In discussing the overall energy distribution of the radiation from an astronomical object, $\log \nu F_\nu$ or $\log \lambda F_\lambda$ is often graphed against $\log \nu$ or $\log \lambda$ to show in what frequency or wavelength regime it emits the most power per decade.

1.1.3 Optical depth

If I is the intensity of a ray of original intensity I_0 which has passed through a layer of absorbing material, then the *optical depth* τ of the

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material is given by

$$I = I_0 \mathrm{e}^{-\tau}.$$

For $\tau = 1$, the ray emerges at $\mathrm{e}^{-1} \simeq 0.368$ times its original strength. More specifically, we can write

$$I_\lambda = I_{\lambda_0} \mathrm{e}^{-\tau_\lambda}.$$

1.2 Blackbodies

1.2.1 *Planck distribution*

A *blackbody* is one which absorbs all the radiation which falls on it, i.e., it has *absorptivity* equal to 1. The *emissivity* of a body is the energy it emits per unit time as a fraction of what it would emit if it were a blackbody.

Kirchhoff's law states that the ratio of the emissivity to the absorptivity of a body at a given wavelength depends only on its temperature and not on its nature.

If an object is to radiate like a blackbody, it must be optically thick at the wavelengths concerned. For example, a dwarf star like our Sun has a well-defined thin layer (the photosphere) whose optical depth is large at visible and ultraviolet wavelengths. A Mira variable, on the other hand, has an extended diffuse atmosphere, and the optical depth at a given radius is a strong function of wavelength, especially in the visible region. Measured at the wavelength of a strong absorption line or band, a Mira appears to have a much larger radius than it has in the continuum.

In the laboratory, blackbody radiation is created as electromagnetic radiation in equilibrium with the walls of an enclosure kept at temperature T, for example, the inside of a furnace with constant-temperature walls. Even if the walls are not perfectly absorbing, so that only some fraction of the incident radiation is absorbed by them, the fact that it is enclosed ensures that the radiation density within is very close to that of a blackbody.

In an astrophysical source, the surface facing the observer can often be regarded as approximating a blackbody of a particular temperature. The emitted spectrum deviates more or less from the true blackbody spectrum according to the variation of the optical depth with wavelength and the temperature gradient near the surface.

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In the case of the surface of a blackbody at temperature T, the specific intensity per unit frequency interval is given by the fundamental relationship, first derived theoretically by Max Planck (1858–1947) in 1900:

$$B_\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sterad^{-1}}.$$

The equivalent in wavelength units is

$$B_\lambda = 10^{-6}\frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}\ \mathrm{W\,m^{-2}\mu m^{-1}sterad^{-1}},$$

where c = velocity of light, h = Planck's constant and k = Boltzmann's constant. The wavelength λ and the constants are in MKS units.

To obtain the monochromatic luminosity *per unit surface area* of a blackbody, B_ν or B_λ must be multiplied by π.

1.2.2 Wien displacement law

The wavelength λ_{peak}, measured in μm, at which the maximum of the blackbody specific intensity, B_λ, occurs, is related to the temperature (in K) by

$$T\lambda_{\mathrm{peak}} = 2898.$$

This relationship is known as the *Wien displacement law.*

Similarly, for frequency units, ν_{max}, the frequency in Hz at which the maximum of B_ν occurs is

$$\nu_{\mathrm{max}} = 5.878 \times 10^{10} T.$$

1.2.3 Rayleigh–Jeans approximation

For the case of wavelengths much longer than that at which B_λ is at a maximum,

$$B_\nu = \frac{2kT}{c^2}\nu^2\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sterad^{-1}}$$

or

$$B_\lambda = 10^{-6}\frac{2ckT}{\lambda^4}\ \mathrm{W\,m^{-2}\mu m^{-1}sterad^{-1}};$$

this is known as the *Rayleigh–Jeans approximation.* In radio astronomy, it is customary to speak of the *antenna temperature* due to a source, based on this law. For a source of uniform surface brightness with angular extent greater than the beamwidth of the antenna, the measured intensity translates directly into a temperature.

Also arising from radio astronomical usage is the *Jansky* as a unit of monochromatic flux density. One Jansky is 10^{-26} W m^{-2} Hz^{-1}.

1.2.4 Stefan's law

The luminosity per unit area of a blackbody is

$$\frac{\sigma T^4}{\pi}$$

where σ is known as Stefan's constant and has the value 5.669×10^{-8} W m^{-2} K^{-4}.

Stefan's constant is obtained by integrating the blackbody distribution function over all frequencies and is given in terms of fundamental physical constants as follows:

$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3}.$$

1.2.5 Radiation density

The energy density u_ν of radiation, or *radiation density*, in a region surrounded by a blackbody of uniform temperature is given by:

$$u_\nu = \frac{4\pi B_\nu}{c}\ \mathrm{J\,m^{-3}\,Hz^{-1}}$$

and, when integrated over frequency,

$$U = \int u_\nu\, \mathrm{d}\nu = \frac{4\sigma}{c} T^4\ \mathrm{J\ m^{-3}},$$

where σ is Stefan's constant.

1.2.6 Infrared colours of blackbodies

Many objects radiate approximately like blackbodies. Some stars have photospheres which approximate a blackbody of a certain temperature and are surrounded by thin dust shells which radiate like blackbodies of a lower temperature. The accompanying Table 1.2 lists the broad-band infrared colors of some representative blackbodies.

Table 1.2. *Broad-band colors of blackbodies*

Temp (K)	*J-H*	*H-K*	*K-L*	*L-N*
300	9.37	6.92	7.69	8.59
400	7.03	5.20	5.66	6.14
500	5.62	4.14	4.43	4.69
600	4.67	3.42	3.60	3.75
800	3.45	2.50	2.56	2.60
1000	2.70	1.93	1.94	1.94
3000	0.63	0.43	0.41	0.42
5000	0.25	0.17	0.16	0.17
10000	0.00	0.00	0.00	0.00

Note: Calculated for the *JHKL* filters used in the SAAO (Carter, 1990) photometric system and a hypothetical *N*-band extending from 8 to 14 μm. The *J*-band is assumed to have a sharp cutoff at 1.37 μm. The color zero-points have been adjusted to be 0.0 for a 10000 K blackbody. The precise color values will differ from system to system (see Section 3.1.4).

1.2.7 Laboratory blackbodies

In a laboratory a "blackbody" calibration source consists of a small oven with walls at a carefuly controlled temperature. Of course, there has to be an aperture somewhere in the wall to allow for the emission of some part of the radiation. The size of the aperture is kept small compared to the total surface area of the cavity, and various shapes have been devised which yield radiation at a pre-determined fraction of what a true blackbody would give at a particular temperature (Treuenfels, 1963). The output beam is uniform over only a small solid angle. See Wolf and Zissis (1978) for many practical details.

1.3 Atomic spectra

In this section a qualitative description of atomic spectra is given in order to provide a "feel" for the considerations involved and the meaning of the terminology. More rigorous accounts will be found in quantum mechanics and spectroscopy textbooks.

A spectral line arises by a transition from one energy state of an atom, E_1, to another, E_2, and its frequency is given by

$$h\nu = E_1 - E_2.$$