

STELLAR ATMOSPHERES



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CHAPTER OVERVIEW

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1.1: Introduction to Radiation Theory

An understanding of any discipline must include a familiarity with and understanding of the words used within that discipline, and the theory of radiation is no exception. The theory of radiation includes such words as radiant flux, intensity, irradiance, radiance, exitance, source function and several others, and it is necessary to understand the meanings of these quantities and the relations between them. The meanings of most of the more commonly encountered quantities and the symbols recommended to represent them have been agreed upon and standardized by a number of bodies, including the International Union of Pure and Applied Physics, the International Commission on Radiation Units and Measurement, the American Illuminating Engineering Society, the Royal Society of London and the International Standards Organization. It is rather unfortunate that many astronomers appear not to follow these conventions, and frequent usages of words such as "flux" and "intensity", and the symbols and units used for them, are found in astronomical literature that differ substantially from usage that is standard in most other disciplines within the physical sciences.

In this chapter I use the standard terms, but I point out when necessary where astronomical usage sometimes differs. In particular I shall discuss the astronomical usage of the words "intensity" and "flux" (which differs from standard usage) in sections 1.12 and 1.14 . Standard usage also calls for SI units, although the older CGS units are still to be found in astronomical writings. Except when dealing with electrical units, this usually gives rise to little difficulty to anyone who is aware that $1 \text{ watt} = 10^7 \text{ erg s}^{-1}$. Where electrical units are concerned, the situation is much less simple.

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1.2: Radiant Flux or Radiant Power, ϕ or P

This is simply the rate at which energy is radiated from a source, in watts.

It is particularly unfortunate that, even with this most fundamental of concepts, astronomical usage is often different. When describing the radiant power of stars, it is customary for astronomers to use the word luminosity, and the symbol L . In standard usage, the symbol L is generally used for the quantity known as radiance, while in astronomical custom, the word "flux" has yet a different meaning. Particle physicists use the word "luminosity" in yet another quite different sense.

The radiant power ("luminosity") of the Sun is $3.85 \times 10^{26} \text{ W}$.

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1.3: Variation with Frequency or Wavelength

The radiant flux per unit frequency interval can be denoted by Φ_ν W Hz⁻¹, or per unit wavelength interval by Φ_λ W m⁻¹. The relations between them are

$$\Phi_\lambda = \frac{\nu^2}{c} \lambda_\nu; \quad \Phi_\nu = \frac{\lambda^2}{c} \Phi_\lambda \quad (1.3.1)$$

It is useful to use a subscript ν or λ to denote "per unit frequency or wavelength interval", but parentheses, for example $\alpha(\nu)$ or $\alpha(\lambda)$, to denote the value of a quantity at a given frequency or wavelength. In some contexts, where great clarity and precision of meaning are needed, it may not be overkill to use both, the symbol $I_\nu(\nu)$, for example, for the radiant intensity per unit frequency interval at frequency ν .

We shall be defining a number of quantities such as flux, intensity, radiance, etc., and establishing relations between them. In many cases, we shall omit any subscripts, and assume that we are discussing the relevant quantities integrated over all wavelengths. Nevertheless, very often the several relations between the various quantities will be equally valid if the quantities are subscripted with ν or λ .

The same applies to quantities that are weighted according to wavelength-dependent instrumental sensitivities and filters to define a *luminous flux*, which is weighted according to the photopic wavelength sensitivity of a defined standard human eye. The unit of luminous flux is the *lumen*. The number of lumens in a watt of monochromatic radiation depends on the wavelength (it is zero outside the range of sensitivity of the eye!), and for heterochromatic radiation the conversion between lumens and watts requires some careful computation. The number of lumens generated by a lightbulb per watt of power input is called the luminous efficiency of the lightbulb. This may seem at first to be a topic of very remote interest, if any, to astronomers, but those who would observe the faintest and most distant galaxies may well at some time in their careers have occasion to discuss the luminous efficiencies of lighting fixtures in the constant struggle against light pollution of the skies.

The topic of lumens versus watts is a complex and specialist one, and we do not discuss it further here, except for one brief remark. When dealing with visible radiation weighted according to the wavelength sensitivity of the eye, instead of the terms radiant flux, radiant intensity, irradiance and radiance, the corresponding terms that are used become luminous flux (expressed in lumens rather than watts), luminous intensity, illuminance and luminance. Further discussion of these topics can be found in section 1.10 and 1.12.

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1.4: Radiant Intensity, I

Not all bodies radiate isotropically, and a word is needed to describe how much energy is radiated in different directions. One can imagine, for example, that a rapidly-rotating star might be nonspherical in shape, and will not radiate isotropically. The *intensity* of a source towards a particular direction specified by spherical coordinates (θ, ϕ) is the radiant flux radiated per unit solid angle in that direction. It is expressed in W sr^{-1} , and the standard symbol is I . In astronomical custom, the word "intensity" and the symbol I are commonly used to describe a very different concept, to which we shall return later.

When dealing with *visible* radiation, we use the phrase *luminous* intensity rather than *radiant* intensity, and the unit is a lumen per steradian, or a candela. At one time, the standard of luminous intensity was taken to be that of a candle of defined design, though the present-day candela (which is one of the fundamental units of the SI system of units) has a different and more precise definition, to be described in section 1.12. The candela and the old standard candle are of roughly the same luminous intensity.

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1.5: Per unit

We have so far on three occasions used the phrase "per unit", as in flux per unit frequency interval, per unit wavelength interval, and per unit solid angle. It may not be out of place to reflect briefly on the meaning of "per unit".

The word *density* in physics is usually defined as "mass per unit volume" and is expressed in kilograms per cubic metre. But do we really mean the mass contained within a volume of a cubic metre? A cubic metre is, after all, a rather large volume, and the density of a substance may well vary greatly from point to point within that volume. Density, in the language of thermodynamics, is an *intensive* quantity, and it is defined *at a point*. What we really mean is the following. If the mass within a volume δV is δm , the *average density* in that volume is $\delta m / \delta V$. The density *at a point* is

$$\lim_{\delta V \rightarrow 0} \frac{\delta m}{\delta V}, \text{ i.e. } \frac{dm}{dV}.$$

Perhaps the short phrase "per unit mass" does not describe this concept with precision, but it is difficult to find an equally short phrase that does so, and the somewhat loose usage does not usually lead to serious misunderstanding.

Likewise, Φ_λ is described as the flux "per unit wavelength interval", expressed in W m^{-1} . But does it really mean the flux radiated in the absurdly large wavelength interval of a metre? Let $\delta\Phi$ be the flux radiated in a wavelength interval $\delta\lambda$. Then

$$\Phi_\lambda = \lim_{\delta\lambda \rightarrow 0} \frac{\delta\Phi}{\delta\lambda}; \text{ i.e. } \frac{d\Phi}{d\lambda}.$$

Intensity is flux "per unit solid angle", expressed in watts per steradian. Again a steradian is a very large angle. What is actually meant is the following. If $\delta\Phi$ is the flux radiated into an elemental solid angle $\delta\omega$ (which, in spherical coordinates, is $\sin\theta \, \delta\theta \, \delta\phi$) then the *average* intensity over the solid angle $\delta\omega$ is $\delta\Phi / \delta\omega$. The intensity *in a particular direction* (θ, ϕ) is

$$\lim_{\delta\omega \rightarrow 0} \frac{\delta\Phi}{\delta\omega}.$$

That is,

$$I = \frac{d\Phi}{d\omega}.$$

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1.6: Relation between Flux and Intensity

For an isotropic radiator,

$$\Phi = 4\pi I. \quad (1.6.1)$$

For an anisotropic radiator

$$\Phi = \int I d\omega, \quad (1.6.2)$$

the integral to be taken over an entire sphere. Expressed in spherical coordinates, this is

$$\Phi = \int_0^{2\pi} \int_0^\pi I(\theta, \phi) \sin \theta d\theta d\phi. \quad (1.6.3)$$

If the intensity is axially symmetric (i.e. does not depend on the azimuthal coordinate ϕ) equation 1.6.3 becomes

$$\Phi = 2\pi \int_0^\pi I(\theta) \sin \theta d\theta. \quad (1.6.4)$$

These relations apply equally to subscripted flux and intensity and to luminous flux and luminous intensity.

Example:

Suppose that the intensity of a light bulb varies with direction as

$$I(\theta) = 0.5I(0)(1 + \cos \theta) \quad (1.6.5)$$

(Note the use of parentheses to mean "at angle θ ".)

Draw this (preferably accurately by computer - it is a *cardioid*), and see whether it is reasonable for a light bulb. Note also that, if you put $\theta = 0$ in equation 1.6.5, you get $I(\theta) = I(0)$.

Show that the total radiant flux is related to the forward intensity by

$$\Phi = 2\pi I(0) \quad (1.6.6)$$

and also that the flux radiated between $\theta = 0$ and $\theta = \pi/2$ is

$$\Phi = \frac{3}{2}\pi I(0). \quad (1.6.7)$$

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1.7: Absolute Magnitude

The subject of magnitude scales in astronomy is an extensive one, which is not pursued at length here. It may be useful, however, to see how magnitude is related to flux and intensity. In the standard usage of the word flux, in the sense that we have used it hitherto in this chapter, flux is related to absolute magnitude or to intensity, according to

$$M_2 - M_1 = 2.5 \log(\Phi_1/\Phi_2) \quad (1.7.1)$$

or

$$M_2 - M_1 = 2.5 \log(I_1/I_2) \quad (1.7.2)$$

That is, the difference in magnitudes of two stars is related to the logarithm of the ratio of their radiant fluxes or intensities.

If we elect to define the zero point of the magnitude scale by assigning the magnitude zero to a star of a specified value of its radiant flux in watts or intensity in watts per steradian, equations 1.7.1 and 1.7.2 can be written

$$M = M_0 - 2.5 \log \Phi \quad (1.7.3)$$

or to its intensity by

$$M = M_0' - 2.5 \log I \quad (1.7.4)$$

If by Φ and I we are referring to flux and intensity integrated over all wavelengths, the absolute magnitudes in equations 1.7.1 to 1.7.4 are referred to as absolute *bolometric* magnitudes. Practical difficulties dictate that the setting of the zero points of the various magnitude scales are not quite as straightforward as arbitrarily assigning numerical values to the constants M_0 and M_0' and I do not pursue the subject further here, other than to point out that M_0 and M_0' must be related by

$$M_0' = M_0 - 2.5 \log 4\pi = M_0 - 2.748. \quad (1.7.5)$$

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1.8: Normal Flux Density F

The rate of passage of energy per unit area normal to the direction of energy flow is the normal flux density, expressed in W m^{-2} .

If a point source of radiation is radiating isotropically, the radiant flux being Φ , the normal flux density at a distance r will be Φ divided by the area of a sphere of radius r . That is

$$F = \Phi / (4\pi r^2) \quad (1.8.1)$$

If the source of radiation is not isotropic (or even if it is) we can express the normal flux density in some direction at distance r in terms of the intensity in that direction:

$$F = I / r^2 \quad (1.8.2)$$

That is, the normal flux density from a point source falls off inversely with the square of the distance.

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1.9: Apparent Magnitude

Although it is not the purpose of this chapter to discuss astronomical magnitude scales in detail, it should be evident that, just as intensity is related to absolute magnitude (both being intrinsic properties of a star, independent of the distance of an observer), so normal flux density is related to apparent magnitude, and they both depend on the distance of observer from star. The relationship is

$$m_2 - m_1 = 2.5 \log(F_1/F_2) \quad (1.9.1)$$

We could in principle set the zero point of the scale by writing

$$m = m_0 - 2.5 \log F \quad (1.9.2)$$

and assigning a numerical value to m_0 , so that there would then be a one-to-one correspondence between normal flux density in W m^{-2} and apparent magnitude. If we are dealing with normal flux density **integrated over all wavelengths**, the corresponding magnitude is called the apparent *bolometric* magnitude.

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1.10: Irradiance E

Suppose that some surface is being irradiated from a point source of radiation of intensity $I \text{ W sr}^{-1}$ at a distance r . The normal flux density ("normal" meaning normal to the direction of propagation), as we have seen, is I/r^2 . If the surface being irradiated is inclined so that its normal is inclined at an angle θ to the line joining it to the point source of radiation, the rate at which radiant energy is falling on unit area of the surface will be $I \cos \theta / r^2$.

In any case, the rate at which radiant energy is falling upon unit area of a surface is called the *irradiance* of that surface. It is denoted by the symbol E , and the units are W m^{-2} . In the simple geometry that we have described, the relation between the intensity of the source and the irradiance of the surface is

$$E = (I \cos \theta) / r^2 \quad (1.10.1)$$

If we are dealing with visible radiation, the number of lumens falling per unit area on a plane surface is called the *illuminance*, and is expressed in lumens per square metre, or *lux*. Recall that a lumen is the SI unit of luminous flux, and the candela is the unit of luminous intensity, and that an isotropic point source of light radiating with a luminous intensity of $I \text{ cd}$ (that is, $I \text{ lm sr}^{-1}$) emits a total luminous flux of $4\pi \text{ lm}$. The relation between the illuminance of a surface and the luminous intensity of a source of light is the same as the relation between irradiance and radiant intensity, namely, equation 1.10.1, or, if the surface is being illuminated normally, equation 1.8.2. If the luminous intensity of a source of light in some direction is one candela, the irradiance of a point on a surface that is closest to the source is 1 lm m^{-2} if the distance is one metre, 1 lm cm^{-2} if the distance is one cm, and 1 lm ft^{-2} if the distance is one foot. A lumen per square metre is a **lux**, and a lumen per square cm is a **phot**. A lumen per square foot is often (usually!) given the extraordinary name of a "foot-candle". This is a most illogical misuse of language, and is mentioned here only because the term is still in frequent use in non-scientific circles. Lumen, candela and lux are, respectively, the SI units of luminous flux, luminous intensity and illuminance. Phot and "foot-candle" are non-SI units of illuminance. The exact definition of the candela will be given in section 1.12; the lumen and lux are derived from the candela. Those who are curious about other strange-sounding units encountered in the quantitative measurement of the visible portion of radiation will also find the definition of "stilb" in section 1.12.

? Example 1.10.1

A table is being illuminated by a light bulb fixed at a distance h vertically above the table. The fixture is such that the socket is above the bulb, and the luminous intensity of the bulb varies as

$$I(\theta) = \frac{1}{2} I(0)(1 + \cos \theta) \quad (1.10.2)$$

where θ is the angle from the downward vertical from the bulb. Show that the illuminance at a point on the table at an angular distance θ from the sub-bulb point is

$$E(\theta) = \frac{1}{2} E(0) (\cos^3 \theta + \cos^4 \theta) \quad (1.10.3)$$

For what angle θ does the irradiance fall to half of the illuminance at the sub-bulb point??

? Example 1.10.2

If the table in the above problem is a circular table whose radius subtends an angle α at the bulb, show that the flux that it intercepts is

$$\Phi(\alpha) = \pi I(0) \left(1 - \cos \alpha + \frac{1}{2} \sin^2 \alpha \right) \quad (1.10.4)$$

What is this if $\alpha = 0$ and if $\alpha \rightarrow \pi/2$? Is this what you would expect? (Compare equation 1.6.7.)

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