

Chapter 2

The Interstellar Radiation Field

2.1 Introduction

The distribution of radiation in the Galaxy varies greatly with the observed wavelength, reflecting the enormous differences of the physical processes responsible for the radiation field. Optical observations of the Milky Way show a stellar component similar to the one of the galaxy shown in Fig. 1.1, concentrated in a relatively thin disk and in a bright bulge. Infrared observations around 25–60 μm and 1.2–3.4 μm obtained with the *Cosmic Background Explorer* (COBE) satellite reveal a thinner layer mainly composed of gas and dust. These layers have a dramatic effect on distant objects, completely extinguishing visible light in some directions. However, at shorter wavelengths, typical of high-energy radiation, and besides scattered point sources, a diffuse radiation is observed spreading across the Galaxy.

In a more quantitative way, the main features of the interstellar radiation field are schematically described in Fig. 2.1, from radio wavelengths to high-energy radiation.

In this figure, the frequency ν (Hz) is on the x -axis and νU_ν is on the y -axis, where U_ν ($\text{erg cm}^{-3} \text{ Hz}^{-1}$) is the energy density per frequency interval. Since we have

$$\int U_\nu d\nu = \int \nu U_\nu d \ln \nu, \quad (2.1)$$

the quantity νU_ν represents the radiation field energy density per frequency logarithmic interval. The principal spectral regions in the figure are:

- A: Radio-integrated radiation
- B: Cosmic background radiation, with a temperature of 2.7 K
- C: Infrared radiation, including galactic and extragalactic contributions, with a major component due to thermal emission of the interstellar dust grains (Chap. 9)
- D: Ultraviolet integrated stellar radiation, the main subject of this chapter, with a cut at $\nu = 3.29 \times 10^{15} \text{ Hz}$ or $\lambda = 912 \text{ \AA}$
- E: High-energy diffuse radiation, meaning X- and γ -rays of galactic and extragalactic origin

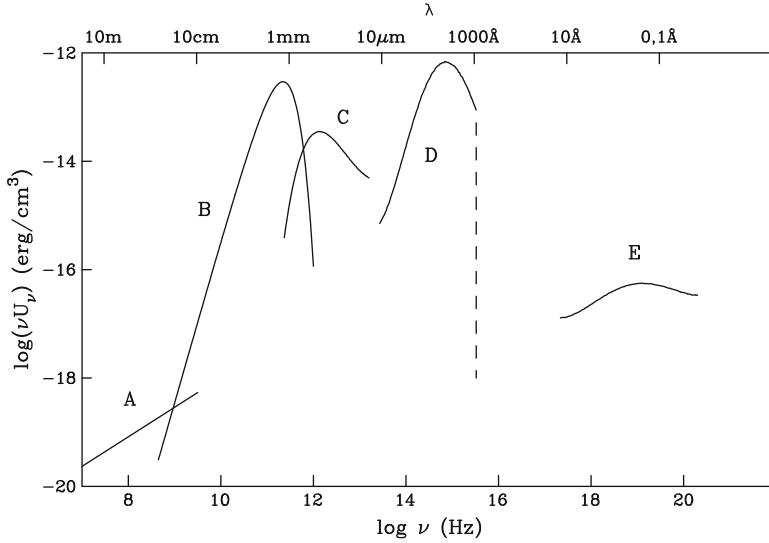


Fig. 2.1 A compilation of the interstellar radiation field from radio waves to gamma rays

2.2 Radio-Frequency Integrated Radiation

Part of the observed radio-frequency radiation comes from extragalactic sources, and we will not discuss them in this book. The major part, however, including the neutral H 21 cm (1,420 MHz) line, is of galactic origin, being produced by several relatively well-known mechanisms. We will present a summary of the main characteristics of these processes. For more details, see Rybicki and Lightman (1979).

2.2.1 Bremsstrahlung Radiation

This is a kind of continuum radio radiation emitted by a plasma through free-free transitions of H and He ions. This radiation is produced in H II regions with electron density $n_e \lesssim 10^{-5} \text{ cm}^{-3}$, electron temperature $T_e \sim 10^3 - 10^4 \text{ K}$, and ratio density between electrons and H atoms $n_e/n_H \gg 1$.

Plasma emissivity, defined as the total power emitted per unit volume per unit solid angle per unit frequency interval between ν and $\nu+d\nu$, is given by

$$\epsilon_\nu = \frac{n_e}{4\pi} \int P(v, \nu) f(v) dv, \quad (2.2)$$

and it is generally measured in $\text{erg cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$, where $f(v)$ is the distribution function of electron velocities and $P(v, \nu)$ is the total power emitted per unit

frequency interval during the collision between an electron with velocity v and an ion with density n_i . If $f(v)$ is given by the Maxwellian distribution, the emissivity is

$$\epsilon_v dv = \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{Z_i^2 e^6}{m_e^2 c^3} \left(\frac{m_e}{kT_e} \right)^{1/2} n_i n_e g_{\text{ff}}(v, T_e) e^{-h\nu/kT_e} dv. \quad (2.3)$$

In this equation, Z_i is the atomic number of the ions, c is the speed of light in vacuum, e is the electron charge, m_e is the electron mass, h is the Planck constant, k is the Boltzmann constant, and g_{ff} is the Gaunt factor, a function that varies slowly with frequency. For $h\nu/kT_e \ll 1$, the Gaunt factor is given by

$$g_{\text{ff}}(v, T_e) = \frac{\sqrt{3}}{\pi} \left[\ln \frac{(2kT_e)^{3/2}}{\pi e^2 v m_e^{1/2}} - \frac{5\gamma}{2} \right], \quad (2.4)$$

where $\gamma = 0.577$ is the Euler constant. Numerically, we have

$$g_{\text{ff}}(v, T_e) = 9.77 \left(1 + 0.130 \log \frac{T_e^{3/2}}{v} \right), \quad (2.5)$$

with v in Hz. For $h\nu \ll kT_e$, $\epsilon_v \propto n_i n_e T_e^{-1/2}$, neglecting the variations in the Gaunt factor.

The total luminosity per unit volume of a plasma for free–free emission is given by

$$L = 4\pi \int \epsilon_v dv = \frac{32\pi e^6}{3m_e c^3 h} \left(\frac{2\pi kT_e}{3m_e} \right)^{1/2} n_i n_e Z_i^2 \bar{g}_{\text{ff}}, \quad (2.6)$$

with units of $\text{erg cm}^{-3} \text{s}^{-1}$ and a mean value of the Gaunt factor $\bar{g}_{\text{ff}} \simeq 1.1 - 1.5$. The absorption coefficient for electron–ion bremsstrahlung is

$$k_v = \frac{\epsilon_v}{B_v(T_e)} = \frac{4}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{Z_i^2 e^6 n_i n_e g_{\text{ff}}}{m_e^{3/2} c (kT_e)^{3/2} v^2}, \quad (2.7)$$

given in cm^{-1} , where we use (2.3) and the Rayleigh–Jeans approximation for the Planck function (Chap. 3). Applying (2.4), we have

$$k_v = 0.1731 \left(1 + 0.130 \log \frac{T_e^{3/2}}{v} \right) \frac{Z_i^2 n_i n_e}{T_e^{3/2} v^2}. \quad (2.8)$$

Finally, if we neglect the g_{ff} dependency on v and T_e , we obtain

$$k_\nu \propto \frac{n_i n_e}{T_e^{3/2} \nu^2}. \quad (2.9)$$

We can introduce the optical depth of free-free radiation if we integrate along the whole extension l of the source,

$$\tau_\nu = \int k_\nu dl \propto T_e^{-3/2} \nu^{-2} \int n_e^2 dl, \quad (2.10)$$

where we consider $n_i = n_e$. The integral along the line of sight is named *emission measure*,

$$\text{EM} = \int n_e^2 dl, \quad (2.11)$$

generally given in pc cm^{-6} . In a more quantitative way, the optical depth can be described by the expression

$$\tau_\nu = 8.235 \times 10^{-2} a(\nu, T_e) T_e^{-1.35} \nu^{-2.1} \text{EM}, \quad (2.12)$$

valid for $h\nu/kT_e \ll 1$ and $T_e < 9 \times 10^5 \text{ K}$, where $a(\nu, T_e)$ is a function that varies slowly with frequency and temperature, T_e is in K, ν is in GHz, and the emission measure is in pc/cm^6 .

2.2.2 Synchrotron Radiation (*Magnetobremssstrahlung*)

This is a type of nonthermal radiation, emitted by relativistic electrons being deflected by the magnetic field of the interstellar medium. It occurs in the diffuse interstellar medium and in supernova remnants.

A relativistic electron with energy E deflected by a magnetic field of intensity B moves along a spiral and emits radiation in a cone with angle $\phi = mc^2/E$ in the form of pulses that produce a continuum spectrum. The emissivity of a group of electrons is

$$\epsilon_\nu = \frac{1}{4\pi} \int P(\nu, E) N(E) dE, \quad (2.13)$$

where P is the emitted power per unit frequency interval for an electron and $N(E)dE$ is the number of electrons with energy between E and $E+dE$ per unit volume along the light of sight. According to the observations, the distribution function of cosmic electrons can be approximately given by

$$N(E) dE = KE^{-\gamma} dE. \quad (2.14)$$

Typical values are $\gamma \simeq 2.6$ and $K \simeq 3.3 \times 10^{-17} \text{ erg}^{\gamma-1} \text{ cm}^{-3}$ for a typical field of $B \simeq 3 \times 10^{-6} \text{ Gauss}$. If the electron distribution is homogeneous and isotropic and the magnetic field is also homogeneous, then we have

$$\epsilon_v = K\alpha(\gamma) \frac{\sqrt{3}}{8\pi} \frac{e^3}{m_e c^2} \left[\frac{3e}{4\pi m_e^3 c^5} \right]^{(\gamma-1)/2} B^{(\gamma+1)/2} \nu^{-(\gamma-1)/2}, \quad (2.15)$$

where $\alpha(\gamma)$ is a slow varying function of the order of one.

2.2.3 Line Radiation

Besides continuum radiation, several lines are also observed at radio wavelengths such as (1) the neutral H 21 cm line, produced in diffuse interstellar clouds and in regions along the Galaxy's spiral arms; (2) lines of various molecules, produced by thermal or maser emission, and (3) recombination lines, produced by H and He and formed by electron recombination in high-energy levels ($n > 50$). The study of interstellar emission lines will be addressed in Chaps. 3 and 4.

2.3 Cosmic Background Radiation

The cosmic background radiation was discovered in 1965 by Penzias and Wilson, researchers at Bell Telephone Laboratories, New Jersey, USA. This discovery, as frequently happens, was made quite by accident. Penzias and Wilson were doing 7 cm radio observations and after subtraction of all known sources they noticed a residual signal whose nature was unknown. At the same time, a team of Princeton University predicted that some radiation should be observed at that exact wavelength, as a result of theoretical models for the formation of the Universe. This radiation would essentially be the remnant of the Big Bang, the explosion that gave birth to the Universe. According to this prediction, the radiation field would be isotropic and would correspond to a blackbody microwave emission with temperature of around 2.7 K.

Atmospheric absorption at $\lambda < 6 \text{ mm}$ prevents observation from the ground of the points next to the maximum of the Planck curve. Until some years ago, just indirect evidence, given by CN molecule observations, pointed to the fact that this maximum existed at all. Since 1975, observations using air balloons and rockets allowed the determination of the curve for shorter wavelengths. Recently, results of the COBE satellite have led to the accurate determination of the complete curve, and nowadays, small temperature anisotropies, of the order of 10^{-5} , have been detected with

important consequences for the Big Bang standard model and the formation of structures in the Universe. Apart from being very important to cosmological studies, the cosmic background radiation also bears a great significance for the present text because at any point of the interstellar medium, this radiation corresponds, at least, to the radiation of a blackbody with temperature 2.7 K.

2.4 Integrated Radiation Field

The interstellar radiation field in the optical and ultraviolet comes essentially from integrated stellar radiation and bears special significance for the study of the interstellar medium. Photons with wavelengths shorter than 2,000 Å play an important role in the ionization of elements, as well as in the heating of dust grains in interstellar clouds.

Near $\lambda = 912 \text{ Å}$ (Lyman limit), there is a cut in the number of available photons because H, the most abundant element, absorbs most of these photons. The column density of neutral H near the galactic plane can reach values of the order of $N_{\text{H}} \sim 10^{20} - 10^{21} \text{ cm}^{-2}$. Since the absorption cross section near the Lyman limit is of the order of $\sigma_{\text{H}} \sim 6.3 \times 10^{-18} \text{ cm}^2$, the optical depth is

$$\tau_{\text{H}} \simeq N_{\text{H}} \sigma_{\text{H}} \simeq 6.3 \times 10^2 - 6.3 \times 10^3 \gg 1, \quad (2.16)$$

so, all the radiation emitted at $\lambda \leq 912 \text{ Å}$ is absorbed near the source. Since the absorption cross section is proportional to λ^3 , the quanta with wavelengths shorter than 100 Å are not completely absorbed anymore, and thus, an X-ray radiation field is observed. Above 912 Å photons can, for instance, ionize elements for which the ionization potential is less than 13.6 eV.

The stellar radiation field can be computed if we know its spatial density or the number of stars of each spectral type and the flux (or energy density) emitted by each stellar type, taking into account the modifications due to interstellar extinction. In the ultraviolet region, the field is essentially determined by hot stars, with spectral types earlier than K.

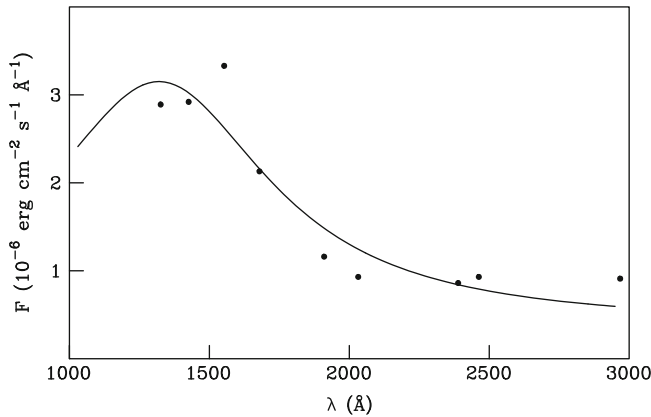
Calculations of the energy density at an average point of the interstellar medium, that is, a point which is not very close to any star, have been made since the 1930s, having greatly progressed since the 1970s when ultraviolet observations allowed their calibration and consequently the refinement of the theoretical models.

The radiation flux in the interstellar medium can be approximated by an ensemble of black bodies, affected by a dilution factor due to the dilution of the radiation over great distances. For instance, the model proposed by Werner and Salpeter (1969) can be written as

$$F_{\lambda} \simeq \sum_1^4 W_i B_{\lambda}(T_i). \quad (2.17)$$

Table 2.1 Coefficients of the Werner and Salpeter (1969) model for the interstellar radiation field

T_i (K)	14,500	7,500	4,000	2.7
W_i	4×10^{-16}	1.5×10^{-14}	1.5×10^{-13}	1

**Fig. 2.2** The UV interstellar radiation field. *Dots* are satellite data and the *curve* shows a simple theoretical model

The values of the fluxes and the dilution factors of each of the four components are listed in Table 2.1.

More accurately, we must consider the real flux distributions, as well as a detailed analysis of the interstellar dust distribution, responsible for extinction. With the development of ultraviolet satellites (OAO, TD-1, Copernicus, IUE), the radiation field in this once inaccessible region has become well known. For instance, Witt and Johnson (1973) used OAO-2 observations to determine the field between 1,250 and 4,250 Å, and other works have complemented and extended these calculations until the 1990s.

Figure 2.2 shows an example of a recent model for the interstellar radiation field in the wavelength interval $1,000 < \lambda(\text{Å}) < 3,000$. The curve shows a recent theoretical model, and the points represent observational data obtained with ultraviolet satellites.

In a general way, the agreement between the models and the observational data is quite good, and the calculated fluxes are of the same order of magnitude of the observed fluxes, $F_\lambda \simeq 1\text{--}3 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ for the considered wavelengths. Meanwhile, the flux distribution with galactic latitude is not entirely satisfactory, which is attributed to an unrealistic parameterization of the stellar distribution with galactic latitude and is a reflex of the non-homogeneity distribution of the interstellar matter.

2.5 Radiative Transfer

2.5.1 Radiative Transfer Equation

Let us consider the problem of radiative transfer in the interstellar field radiation and estimate the field energy density at a point in the galactic disk, influenced by stars, gas, and dust. If we assume the Galaxy to be a flat disk, the radiation-specific intensity I_ν ($\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$) at a given frequency is only a function of the height to the galactic plane, z . The one-dimensional steady-state radiative transfer equation without induced emissions and with coherent and isotropic scattering may be written as

$$\mu \frac{dI_\nu}{dz} = j_\nu - (k_\nu + \sigma_\nu)I_\nu + \sigma_\nu J_\nu, \quad (2.18)$$

where $\mu = \cos \theta$, θ being the angle between the direction of the beam propagation and the normal to the considered element; j_ν is the emission coefficient per volume ($\text{erg cm}^{-3} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$); k_ν is the absorption coefficient per volume (cm^{-1}); σ_ν is the scattering coefficient per volume (cm^{-1}); and J_ν is the radiation mean intensity. Let us define the optical depth by the expression

$$d\tau_\nu = (k_\nu + \sigma_\nu)dz = k_E dz, \quad (2.19)$$

where k_E is the total extinction coefficient. Let us take $\tau = 0$ at $z = 0$ and $\tau = \tau_H$ at $z = H$, the scale height of the disk. Replacing in (2.18), we have

$$\mu \frac{dI_\nu}{d\tau_\nu} = \frac{j_\nu}{k_\nu + \sigma_\nu} - I_\nu + \frac{\sigma_\nu}{k_\nu + \sigma_\nu} J_\nu, \quad (2.20)$$

which can be simplified to

$$\mu \frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu + \gamma_\nu J_\nu, \quad (2.21)$$

where we define the dust grain albedo as

$$\gamma_\nu = \frac{\sigma_\nu}{k_\nu + \sigma_\nu} \quad (2.22)$$

and the source function as

$$S_\nu = \frac{j_\nu}{k_\nu + \sigma_\nu}. \quad (2.23)$$

Let us consider the part of the observed optical spectrum where emission essentially comes from the Galaxy's stars. Let n_*^s be the stellar density (cm^{-3} or pc^{-3}) of stars of spectral type s and L_ν^s the luminosity ($\text{erg s}^{-1} \text{Hz}^{-1}$) of these stars in the frequency interval between ν and $\nu+d\nu$. We may write

$$j_\nu = \frac{1}{4\pi} \sum n_*^s L_\nu^s, \quad (2.24)$$

where the summation must be extended to all the stars that contribute to the considered frequency interval.

2.5.2 Transfer Equation Solution

Let us consider the solution of (2.21) using the two-beam Schuster approximation (1905, see also Mihalas 1978). In this case, we define

$$I_\nu^+ = \int_0^{\pi/2} I_\nu \sin \theta d\theta = \int_0^1 I_\nu d\mu \quad (0 \leq \mu \leq 1) \quad (2.25a)$$

$$I_\nu^- = \int_{\pi/2}^\pi I_\nu \sin \theta d\theta = \int_{-1}^0 I_\nu d\mu \quad (-1 \leq \mu \leq 0) \quad (2.25b)$$

Recalling that $\mu = 1$ for $\theta = 0$, $\mu = 0$ for $\theta = \pi/2$, and $\mu = -1$ for $\theta = \pi$. In this case, I_ν^+ and I_ν^- are independent of μ and

$$\begin{aligned} J_\nu &= \frac{1}{4\pi} \int I_\nu d\omega = \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_0^\pi I_\nu \sin \theta d\theta \\ &= \frac{1}{2} \int_0^\pi I_\nu \sin \theta d\theta = \frac{1}{2} \int_{-1}^1 I_\nu d\mu \\ &= \frac{1}{2} \int_{-1}^0 I_\nu d\mu + \frac{1}{2} \int_0^1 I_\nu d\mu \\ &= \frac{1}{2} (I_\nu^+ + I_\nu^-), \end{aligned} \quad (2.26)$$

where we use $d\omega = \sin \theta d\theta d\phi$ for the solid angle element around the considered direction. In the same way, the flux F_ν is given by

$$F_\nu = \frac{1}{\pi} \int I_\nu \cos \theta d\omega = 2 \int_{-1}^1 I_\nu \mu d\mu = I_\nu^+ - I_\nu^-. \quad (2.27)$$

By analogy, this expression may be written as

$$F_v = F_v^+ - F_v^-, \quad (2.28)$$

where we define

$$F_v^+ = 2 \int_0^1 I_v \mu \, d\mu \quad (2.29a)$$

and

$$F_v^- = -2 \int_{-1}^0 I_v \mu \, d\mu. \quad (2.29b)$$

Multiplying (2.21) by $d\mu$, integrating between 0 and 1, and applying (2.27) and (2.28), we obtain

$$\begin{aligned} \frac{d}{d\tau_v} \int_0^1 I_v \mu \, d\mu &= S_v \int_0^1 d\mu - \int_0^1 I_v \, d\mu + \gamma_v J_v \int_0^1 d\mu \\ \frac{1}{2} \frac{dI_v^+}{d\tau_v} &= S_v - I_v^+ + \gamma_v J_v, \end{aligned} \quad (2.30)$$

where we assume the homogeneous case, in which j_ν , k_ν , σ_ν , and γ_ν are independent of μ . In the same way, multiplying (2.21) by $d\mu$ and integrating between -1 and 0 ,

$$-\frac{1}{2} \frac{dI_v^-}{d\tau_v} = S_v - I_v^- + \gamma_v J_v. \quad (2.31)$$

Adding and subtracting (2.30) and (2.31) and considering (2.26) and (2.27), we obtain the relations

$$\begin{aligned} \frac{1}{2} \frac{d}{d\tau_v} (I_v^+ - I_v^-) &= 2S_v - (I_v^+ + I_v^-) + 2\gamma_v J_v \\ \frac{dF_v}{d\tau_v} &= 4S_v - 4J_v(1 - \gamma_v) \end{aligned} \quad (2.32)$$

$$\begin{aligned} \frac{1}{2} \frac{d}{d\tau_v} (I_v^+ + I_v^-) &= -(I_v^+ - I_v^-) \\ \frac{dJ_v}{d\tau_v} &= -F_v. \end{aligned} \quad (2.33)$$

Calculating the differential of (2.32) and using (2.33),

$$\frac{d^2 F_v}{d\tau_v^2} = -4(1 - \gamma_v) \frac{dJ_v}{d\tau_v} = 4(1 - \gamma_v)F_v. \quad (2.34)$$

The expression (2.34) is an ordinary linear differential equation of second order, with constant coefficients. Its solution can be written as

$$F_v = A \cosh \left[2(1 - \gamma_v)^{1/2} \tau_v \right] + B \sinh \left[2(1 - \gamma_v)^{1/2} \tau_v \right]. \quad (2.35)$$

Constants A and B can be determined by boundary conditions. For $\tau_v = 0$, we have $F_v(\tau_v) = 0$ and thus $A = 0$. Expression (2.35) then becomes

$$F_v = B \sinh \left[2(1 - \gamma_v)^{1/2} \tau_v \right]. \quad (2.36)$$

From (2.32) and (2.36),

$$J_v = \frac{S_v}{1 - \gamma_v} - \frac{1}{4(1 - \gamma_v)} \frac{dF_v}{d\tau_v}$$

$$\frac{dF_v}{d\tau_v} = 2(1 - \gamma_v)^{1/2} B \cosh \left[2(1 - \gamma_v)^{1/2} \tau_v \right]$$

in such a way that

$$J_v = \frac{S_v}{1 - \gamma_v} - \frac{B}{2(1 - \gamma_v)^{1/2}} \cosh \left[2(1 - \gamma_v)^{1/2} \tau_v \right]. \quad (2.37)$$

Applying the second boundary condition at the edge of the disk, where there is no incident radiation, we have $\tau_v = \tau_{vH}$ for $z = H$. From (2.26) and (2.27)

$$J_v(\tau_{vH}) = \frac{1}{2} I_v^+(\tau_{vH})$$

$$F_v(\tau_{vH}) = I_v^+(\tau_{vH})$$

so that

$$J_v(\tau_{vH}) = \frac{1}{2} F_v(\tau_{vH}). \quad (2.38)$$

From (2.36), (2.37), and (2.38)

$$B = \frac{2S_v}{1 - \gamma_v} \left\{ \sinh \left[2(1 - \gamma_v)^{1/2} \tau_{vH} \right] + \frac{\cosh \left[2(1 - \gamma_v)^{1/2} \tau_{vH} \right]}{(1 - \gamma_v)^{1/2}} \right\}^{-1}. \quad (2.39)$$

When we replace the value of B in (2.36), we may calculate the flux and the mean intensity. Finally, the energy density can be calculated by

$$U_v = \frac{1}{c} \int I_v d\omega = \frac{4\pi}{c} J_v. \quad (2.40)$$

2.5.3 Numerical Example: Energy Density

Let us calculate the energy density at $\lambda = 5,500 \text{ \AA}$, in the middle of the visible spectrum, for a galactic disk model, assuming $2H \simeq 200 \text{ pc}$. The energy density is determined by stars of spectral type earlier than M that tend to concentrate in the region near the disk. In these conditions, the emission coefficient j_{5500} is given by (2.24). The luminosity at $5,500 \text{ \AA}$ can be determined by

$$L_{5500} = f L_{\odot} 10^{0.4(4.83 - M_v)}, \quad (2.41)$$

where M_v is the absolute visual magnitude of the considered star; $L_{\odot} = 3.83 \times 10^{33} \text{ erg s}^{-1}$ is the Sun's luminosity, whose absolute bolometric magnitude is taken to be 4.83; and f is the fraction of stellar radiation in a small wavelength interval centered on $\lambda = 5,500 \text{ \AA}$. Since approximately 93 % of the solar luminosity is concentrated in a bandwidth of about $1,000 \text{ \AA}$ around $5,500 \text{ \AA}$, $f \simeq 0.93 \times 10^{-3} \text{ \AA}^{-1}$. Taking n_*^s in units of pc^{-3} , (2.24) becomes

$$j_{5500} = 9.61 \times 10^{-27} \sum n_*^s 10^{0.4(4.83 - M_v)}. \quad (2.42)$$

Let us consider a typical luminosity function (Allen 1973, p. 247). In this case, the emission coefficient per unit wavelength j_{5500} ($\text{erg cm}^{-3} \text{ s}^{-1} \text{ \AA}^{-1} \text{ sr}^{-1}$) is given in Table 2.2 for the main stellar spectral types.

A more complete study of interstellar extinction will be presented in Chap. 9. For now, we will consider the total extinction coefficient adopting a mean extinction $\Delta m/H \simeq 1 \text{ mag kpc}^{-1}$. As

$$\tau_{5500H} = k_E H = \frac{\Delta m}{1.086}, \quad (2.43)$$

Table 2.2 Average emission coefficients for stars with different spectral types

Spectral type	j_{5500}
O	5.96×10^{-31}
B	9.93×10^{-29}
A	1.01×10^{-28}
F	1.07×10^{-28}
G	8.09×10^{-29}
K	1.25×10^{-28}
M	3.29×10^{-29}
Total	5.47×10^{-28}

we obtain

$$k_E = \frac{\Delta m/H}{1.086} \simeq 2.98 \times 10^{-22} \text{ cm}^{-1} \quad (2.44)$$

and thus $\tau_{5500H} \simeq 9.21 \times 10^{-2}$. As we shall see in Chap. 9, the optical properties of the dust grains, such as the albedo, vary with wavelength in a complex way for different types of solid interstellar particles. Using a typical value of $\gamma_{5500} \simeq 0.2$, we have $\sigma_{5500} \simeq 5.96 \times 10^{-23} \text{ cm}^{-1}$ and $k_{5500} \simeq 2.38 \times 10^{-22} \text{ cm}^{-1}$. The source function is then $S_{5500} \simeq 1.84 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ sr}^{-1}$ and the constant $B \simeq 3.55 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ sr}^{-1}$. The mean intensity J_{5500} in the center of the disk where $\tau_{5500} = 0$ is $J_{5500} \simeq 3.15 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ sr}^{-1}$. Finally, the energy density is $U_{5500} \simeq 1.32 \times 10^{-16} \text{ erg cm}^{-3} \text{ \AA}^{-1}$, which can be compared with the observational value, of the order of $U_{5500} \simeq 0.63 \times 10^{-16} \text{ erg cm}^{-3} \text{ \AA}^{-1}$. Note that this value corresponds to density U_λ . To obtain U_ν , we use the fact that $U_\lambda d\lambda = U_\nu d\nu$, so $U_\nu = (c/\nu^2)U_\lambda = (\lambda^2/c)U_\lambda$. In this case, we have $\nu U_\nu = \lambda U_\lambda \sim 7 \times 10^{-13} \text{ erg cm}^{-3}$ (cf. Fig. 2.1).

2.6 High-Energy Radiation

The origin of high-energy radiation is not very well known. It can comprise an extragalactic component, as well as several galactic sources. The sources may be stable, variable, or even present violent explosions. As for the infrared part of the spectrum, the Galaxy's center presents considerable emission. High-energy radiation is usually divided in classes, according to the detection technique used, from soft X-rays, with energies up to approximately 10 keV, through hard X-rays, with energies up to 100 keV, to high-energy γ -rays, with energies higher than 10 MeV. High-energy detectors have been recently mounted on satellites such as COS-B, COMPTON, and CHANDRA.

Several galactic objects like pulsars, binary systems, novae, and supernovae remnants show high-energy emission. Besides this, there is an extragalactic contribution that includes active galactic nuclei and a non-identified component, attributed to a large number of non-resolved sources, such as supernovae, strong

stellar winds, or a hot intergalactic medium. Finally, γ -rays can also be produced from the interaction between cosmic rays and interstellar gas, forming pions that decay into a pair of γ -rays.

Some of the probable mechanisms responsible for X-ray and γ -ray emission are bremsstrahlung, synchrotron emission, and inverse Compton scattering. The first two were considered in Sect. 2.2. In inverse Compton scattering, a photon (energy $h\nu$) collides with an electron or ion with velocity v and energy $E \gg h\nu$, resulting in energy transfer from the electron to the photon. The energy of the produced quantum is

$$E_\gamma \simeq \gamma^2 h\nu \quad (q \ll 1) \quad (2.45)$$

$$E_\gamma \simeq \gamma m_e c^2 \quad (q \gg 1), \quad (2.46)$$

where

$$q = \frac{\gamma h\nu}{m_e c^2} \quad (2.47)$$

and

$$\gamma = \frac{E}{m_e c^2} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}. \quad (2.48)$$

For instance, if we consider a photon from the stellar radiation field with $\lambda = 5,500 \text{ \AA}$, frequency $\nu = 5.45 \times 10^{14} \text{ Hz}$, and energy $h\nu = 3.62 \times 10^{-12} \text{ erg} = 2.26 \text{ eV}$ interacting with a cosmic electron with energy $E = 1 \text{ GeV}$, we have $\gamma = E/m_e c^2 \simeq 1.95 \times 10^3$, $q \simeq 0.0086 \ll 1$, and $E_\gamma \simeq 1.38 \times 10^{-5} \text{ erg} = 8.59 \text{ MeV}$, corresponding to $\nu_\gamma \simeq 2.08 \times 10^{21} \text{ Hz}$.

Exercises

- 2.1 Show that the cosmic microwave background radiation, remnant of the Big Bang, has a maximum given by the peak of curve B from Fig. 2.1. What is the wavelength corresponding to this maximum?
- 2.2 The emission measure in the direction of an H II region is 10^3 pc/cm^6 and the column density of hydrogen nuclei in the same direction is 10^{20} cm^{-2} . Estimate the electron density and the H II region dimensions.
- 2.3 Use the radiation field model with four components given in Table 2.1 and equation (2.17) and (a) calculate the energy density U_λ in the optical spectrum center, where $\lambda = 5,500 \text{ \AA}$. (b) Compare the result with the mean value obtained from the solution of the transfer equation.

- 2.4 Use the model obtained from the solution of the transfer equation and estimate the flux, the mean intensity, and the energy density in the rim of the galactic disk for $\lambda = 5,500 \text{ \AA}$.
- 2.5 (a) Assume that the radiation field at some point in the interstellar medium can be characterized by a blackbody with $T = 10^4 \text{ K}$ and dilution factor $W = 10^{-14}$. What would be the flux at $\lambda = 2,000 \text{ \AA}$ in $\text{erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$? (b) Compare the result with the value predicted by the four component model described in Sect. 2.4. (c) Which of the two above models better follows the observations, taking into account the observational data shown in Fig. 2.2?

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