Chapter 12

Electromagnetic radiation

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Blackbody radiation (cgs units)

Planck functions (brightness of a blackbody)

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\left(\exp\left(\frac{h\nu}{kT}\right) - 1\right)} \quad \text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}\,\text{sr}^{-1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\left(\exp\left(\frac{hc}{\lambda kT}\right) - 1\right)} \quad \text{erg cm}^{-2}\,\text{s}^{-1}\,\text{cm}^{-1}\,\text{sr}^{-1}$$

$$B_{\tilde{\nu}}(T) = \frac{2hc^2\tilde{\nu}^3}{\left(\exp\left(\frac{hc\tilde{\nu}}{kT}\right) - 1\right)} \quad \text{erg cm}^{-2}\,\text{s}^{-1}\,(\text{cm}^{-1})^{-1}\,\text{sr}^{-1}$$

$$B_\nu(T)\,\mathrm{d}\nu = B_\lambda(T)\,\mathrm{d}\lambda = B_{\tilde{\nu}}(T)\,\mathrm{d}\tilde{\nu}$$

Rayleigh–Jeans law

$h\nu/kT << 1$

$$B_\nu(T) = 2\left(\frac{\nu}{c}\right)^2 kT$$

Wien's law

$h\nu/kT >> 1$

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \exp\left(-\frac{h\nu}{kT}\right)$$

Stefan–Boltzmann law

$$\text{total emittance} = \pi \int_0^\infty B_\nu(T)\,\mathrm{d}\nu = \sigma T^4 \quad \text{erg cm}^{-2}\,\text{s}^{-1}$$

$$\text{where } \sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-5} \quad \text{erg cm}^{-2}\,\text{deg}^{-4}\,\text{s}^{-1}$$

Wien displacement law

Maximizing B_ν:

$\nu_m = 5.9 \times 10^{10} T$ Hz

$\lambda_m = 0.51 T^{-1}$ cm

Maximizing B_λ:

$\nu_m = 10.3 \times 10^{10} T$ Hz

$\lambda_m = 0.29 T^{-1}$ cm

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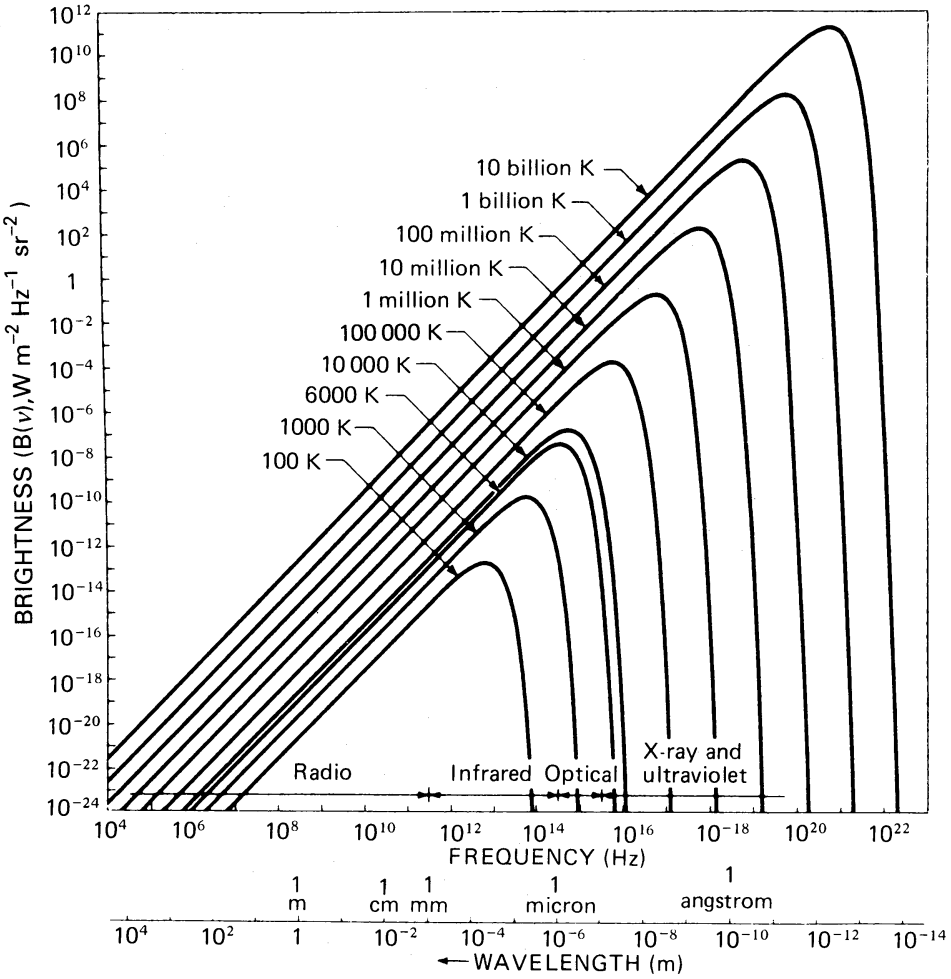
Mean photon energy

$$\langle h\nu \rangle = \frac{\int_0^\infty B_\nu(T)\,d\nu}{\int_0^\infty (B_\nu(T)/h\nu)\,d\nu} = \left(\frac{\zeta(4)}{\zeta(3)}\right)\left(\frac{\Gamma(4)}{\Gamma(3)}\right)kT = 2.7012kT.$$

where $\zeta(n)$ = Riemann zeta function; $\Gamma(n)$ = gamma function.

Radiation curves

Planck-law radiation curves. (Adapted from Kraus, J. D., *Radio Astronomy*, McGraw-Hill Book Company, 1966.)



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Synchrotron radiation (cgs units)

Single electron in a magnetic field

Total radiated power:

$$P = 1.6 \times 10^{-15} \gamma^2 B^2 \beta^2 \sin^2 \alpha \quad \text{erg s}^{-1},$$

where

$\gamma = (1 - \beta^2)^{-1/2} = E/mc^2$,
E = total energy of particle,
$\beta = v/c$,
B = magnetic induction in Gauss,
α = pitch angle, angle between B and velocity vector.

Synchrotron lifetime:

$$t_s = \frac{3 \times 10^8}{\gamma B^2 \beta^2 \sin^2 \alpha} \quad \text{s}.$$

Spectrum:

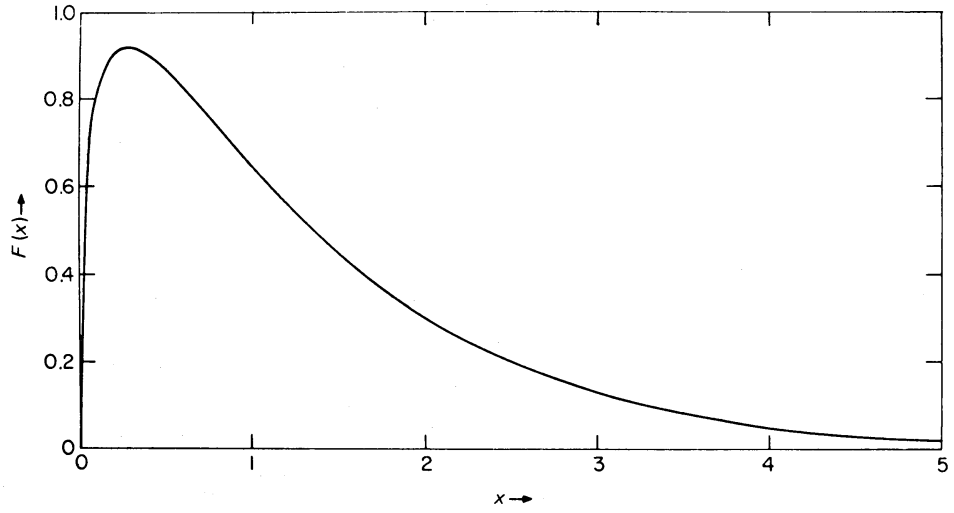
$$P(\nu) = 2.3 \times 10^{-22} B \sin \alpha F(\nu/\nu_c) \quad \text{erg s}^{-1}\,\text{Hz}^{-1} \quad (\alpha >> 1/\gamma).$$

$$\nu_c = 4.3 \times 10^6 B \gamma^2 \sin \alpha \quad \text{Hz} \quad \text{(critical frequency)}.$$

$$F(x) = x \int_x^\infty d\xi K_{5/3}(\xi), \quad x = \nu/\nu_c.$$

$K_{5/3}(\xi)$ is the modified Bessel function of fractional order 5/3.

A plot of the function $F(x)$ or, equivalently, the dimensionless synchrotron spectrum. $F(\nu/\nu_c)$ reaches its maximum value of 0.918 at $\nu_m = 0.29\nu_c$. (Adapted from Tucker, W. H. & Blumenthal, G. R. in *X-ray Astronomy*, R. Giacconi & H. Gursky, eds., D. Reidel Publishing Company, Dordrecht, 1974.)



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General distribution of electrons

$$\frac{dP}{dV\,d\nu} = \iint d\gamma\, d\Omega_\alpha\, n(\gamma,\alpha)P(\nu),$$ the spectral emission per unit volume,

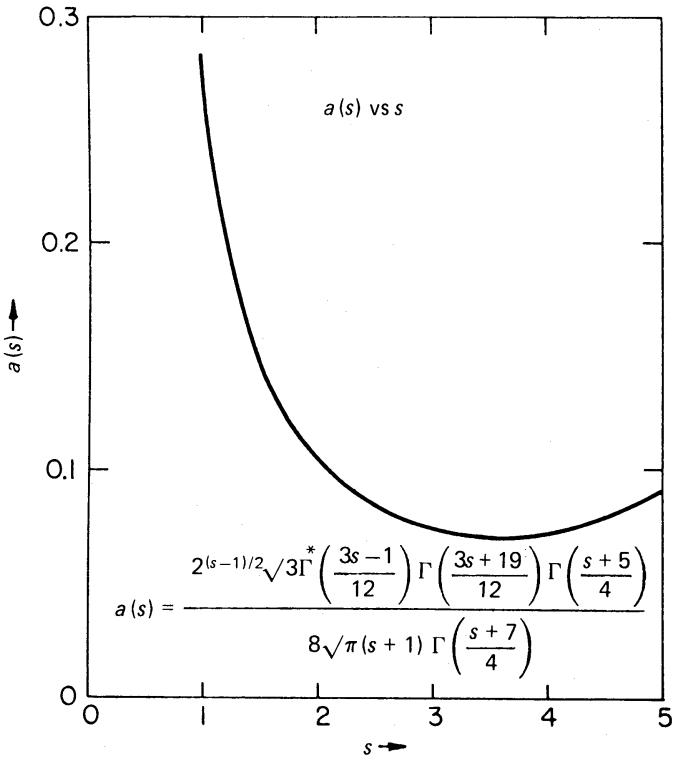
where $n(\gamma,\alpha)\,d\gamma\,d\Omega_\alpha$ = density of electrons with Lorentz factor between γ and $\gamma + d\gamma$ and pitch angle between α and $\alpha + d\alpha$; $d\Omega_\alpha = 2\pi \sin\alpha\, d\alpha$; $P(\nu)$ = single electron spectrum.

Power law distribution of electrons

$$n(\gamma,\alpha) = N\gamma^{-s}g(\alpha)/4\pi,$$

and for local isotropy $g(\alpha) = 1$,

$$\frac{dP}{dV\,d\nu} = 1.7 \times 10^{-21} Na(s)B(4.3 \times 10^6 B/\nu)^{(s-1)/2} \text{ erg s}^{-1}\text{ cm}^{-3}\text{ Hz}^{-1}.$$

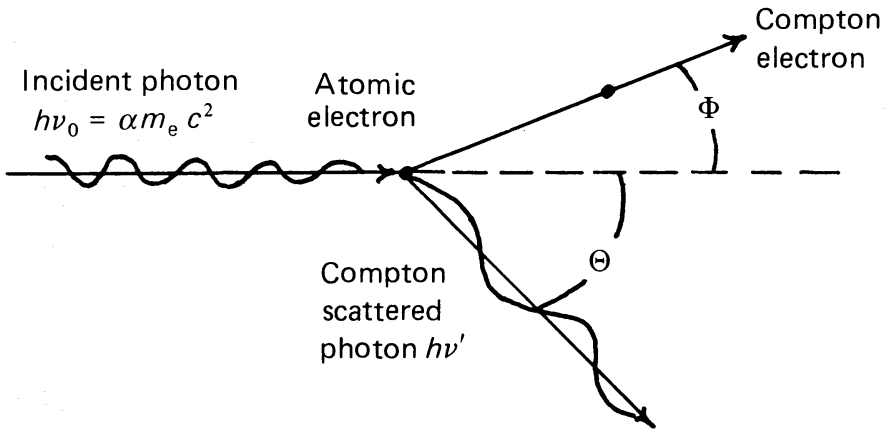


* note: Γ(x) is the gamma function.

(Tucker, W. H. & Blumenthal, G. R., *op. cit.*)

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Compton scattering (cgs units)



Compton shift

$$\frac{c}{\nu'} - \frac{c}{\nu_0} = \lambda' - \lambda_0 = \frac{h}{m_e c}(1 - \cos\theta).$$

Energy of scattered photon

$$h\nu' = \frac{m_e c^2}{1 - \cos\theta + (1/\alpha)}, \quad \alpha = h\nu_0/m_e c^2.$$

Energy of the struck electron

$$T = h\nu' - h\nu_0,$$

$$T = h\nu_0 \frac{\alpha(1 - \cos\theta)}{1 + \alpha(1 - \cos\theta)},$$

$$T_{\max} = \frac{h\nu_0}{1 + (1/2\alpha)}.$$

Relation between the scattering angles, ϕ and θ

$$\cot\phi = (1 + \alpha)\frac{1 - \cos\theta}{\sin\theta} = (1 + \alpha)\tan\frac{\theta}{2}.$$

Klein–Nishina cross-section for unpolarized incident radiation

$$\frac{d\sigma}{d\Omega} = r_0^2\left[\frac{1}{1 + \alpha(1 - \cos\theta)}\right]^3\left(\frac{1 + \cos^2\theta}{2}\right)\left[1 + \frac{\alpha^2(1 - \cos\theta)^2}{(1 + \cos^2\theta)[1 + \alpha(1 - \cos\theta)]}\right]$$

$\text{cm}^2\,\text{electron}^{-1}\,\text{sr}^{-1}$.

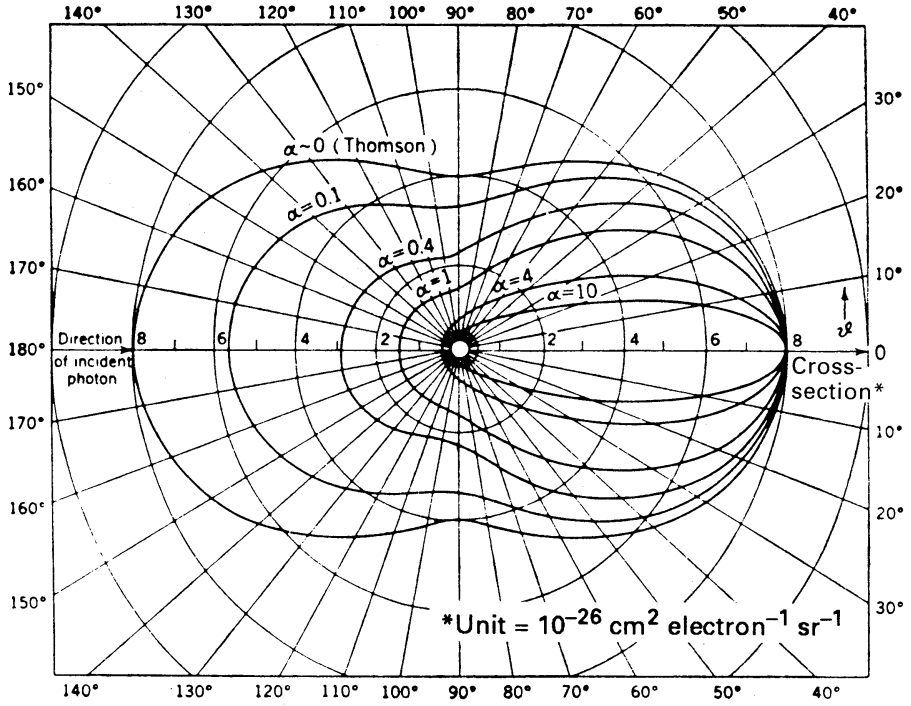
where $r_0 = \dfrac{e^2}{m_e c^2}$, classical electron radius $= 2.82 \times 10^{-13}$ cm.

$$\int \frac{d\sigma}{d\Omega}\,d\Omega = \frac{8\pi}{3} r_0^2(1 - 2\alpha + 5.2\alpha^2 - 13.3\alpha^3 + \cdots) \quad \text{cm}^2\,\text{electron}^{-1}.$$

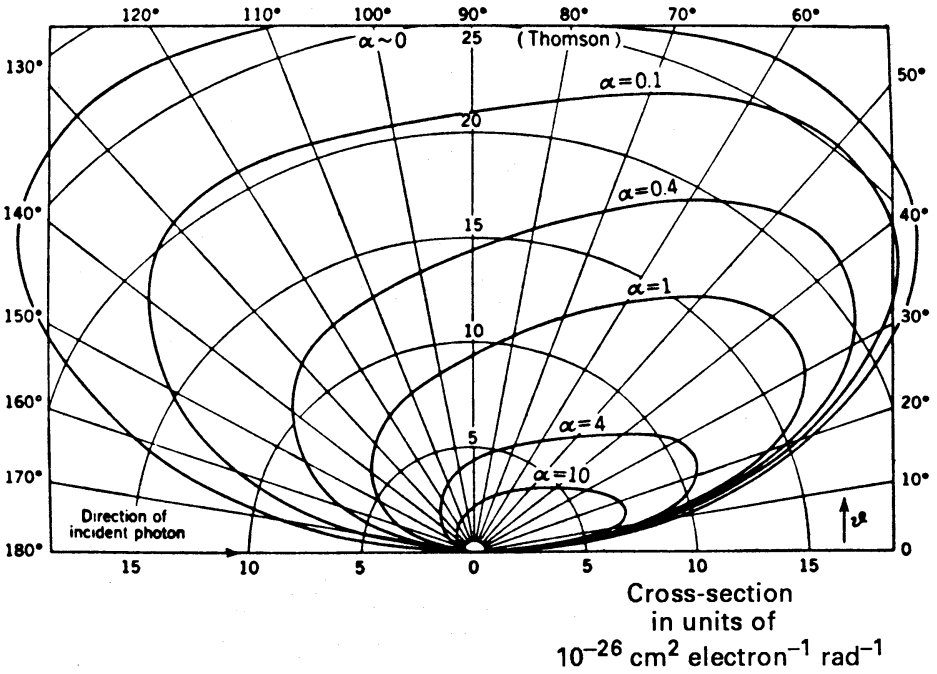
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Klein–Nishina differential cross-sections

Differential cross-sections, $d\sigma(\theta)/d\Omega$, for the production of secondary photons from Compton scattering. Curves are shown for six different values of primary photon energy. (From Davisson & Evans, *Rev. Mod. Phys.*, **34**, 79, 1953.)



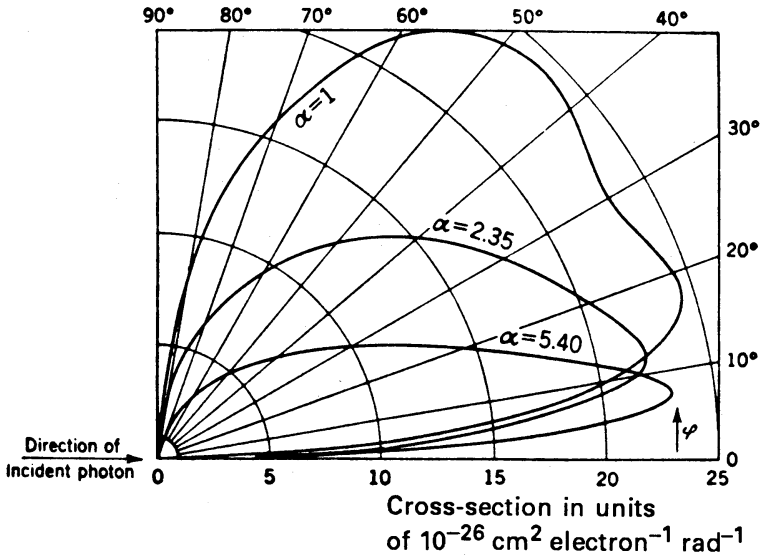
Differential cross-sections, $d\sigma(\theta)/d\theta$, for the production of secondary photons from Compton scattering. (From Davisson & Evans, *Rev. Mod. Phys.*, **34**, 79, 1953.)



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Klein–Nishina differential cross-sections (*cont.*)

Differential cross-sections, $d\sigma_e(\phi)/d\phi$, for the production of secondary electrons from Compton scattering. (From Davisson & Evans, *Rev. Mod. Phys.*, **34**, 79, 1953.)



Inverse Compton scattering (cgs units)

Compton collisions between relativistic electrons and low frequency photons.

Thomson limit

$$\gamma h\nu_0 << m_e c^2,$$

where γ is the Lorentz factor for the relativistic electrons.

Total energy loss rate (Thomson limit)

$$-\frac{dE}{dt} = \tfrac{4}{3}\sigma_T c\gamma^2 u = 2.6 \times 10^{-14}\gamma^2 u \quad \text{erg s}^{-1}\ \text{electron}^{-1},$$

where

u = radiation energy density,

$\sigma_T = \dfrac{8\pi}{3} r_0^2$, the Thomson cross-section,

$r_0 = \dfrac{e^2}{m_e c^2}$.

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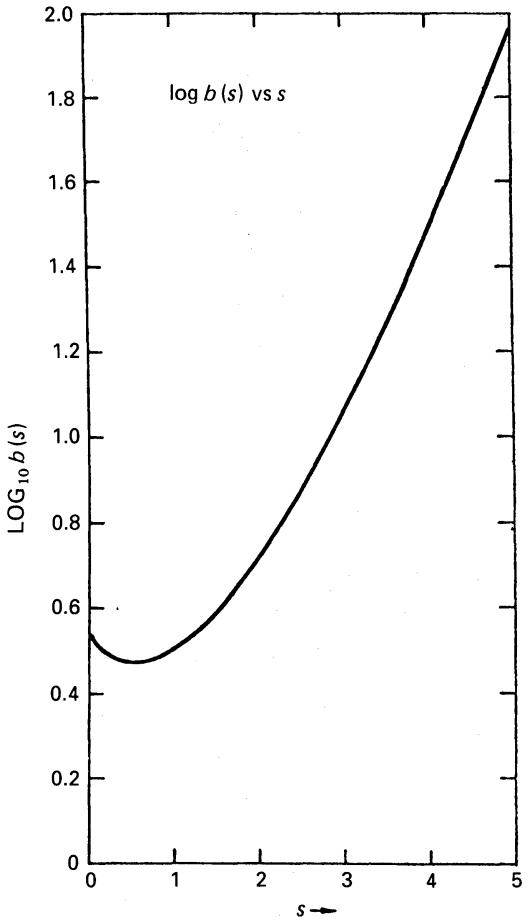
Spectra

Thomson limit – power law electron distribution function and blackbody radiation: when the initial radiation field is given by a blackbody distribution and the density of electrons is given by a power law, viz., $N(\gamma)\,\mathrm{d}\gamma = N\gamma^{-s}\,\mathrm{d}\gamma$ (the density of electrons with a Lorentz factor between γ and $\gamma + \mathrm{d}\gamma$), the spectral power density is:

$$\frac{\mathrm{d}P}{\mathrm{d}V\,\mathrm{d}\nu} = 4.2 \times 10^{-40} N b(s) T^3 (2.1 \times 10^{10} T/\nu)^{(s-1)/2}$$

$$\text{erg cm}^{-3}\,\text{s}^{-1}\,\text{Hz}^{-1},$$

with T in degrees Kelvin.



(Tucker, W. H. & Blumenthal, G. R., *op. cit.*)

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Hot plasma emission (cgs units)

Bremsstrahlung from a hot plasma

For a Maxwellian distribution of electron velocities, the spectral emission per unit volume:

$$\frac{dP_B(T)}{dV\,d\nu} = 6.8 \times 10^{-38} T^{-1/2} e^{-E/kT} N_e N_Z Z^2 \overline{g_B(T,E)} \quad \text{erg cm}^{-3}\,\text{s}^{-1}\,\text{Hz}^{-1},$$

where

N_e = electron density,

N_Z = ion density (charge z),

$E = h\nu$ = photon energy, and

g_B is the Gaunt factor.

$$\overline{g_B(T,E)} \approx \frac{\sqrt{3}}{\pi} \ln\left(\frac{4kT}{\Gamma E}\right), \quad \text{for } E << kT \qquad (\ln\Gamma = 0.577)$$

$$\approx (E/kT)^{-0.4}, \qquad \text{for } E \sim kT.$$

The total bremsstrahlung emission:

$$\frac{dP_B}{dV} = 1.4 \times 10^{-27} T^{1/2} N_e N_Z Z^2 g_B(T) \quad \text{erg cm}^{-3}\,\text{s}^{-1},$$

where $g_B(T) \approx 1.2$.

$$\frac{dP_B}{dV} = 2.4 \times 10^{-27} T^{1/2} N_e^2 \quad \text{erg cm}^{-3}\,\text{s}^{-1}$$

for a plasma with cosmic abundances, since the contribution from all ions

$$\sum N_e N_Z Z^2 \approx 1.4 N_e^2.$$

Non-thermal bremsstrahlung

For a flux density $J(E) = J_0 E^{-s}$ erg cm^{-2} s^{-1} erg^{-1} of non-thermal electrons, the spectral emission per unit volume:

$$\frac{dP_B}{dV\,d\nu} = 1.2 \times 10^{-6} Z^2 N_Z J_0 \frac{E^{-s-1}}{s} \quad \text{erg cm}^{-3}\,\text{s}^{-1}\,\text{Hz}^{-1}.$$

X-ray line emission from a hot plasma (electron collisional excitation)

For a Maxwellian distribution of electron velocities, the power emitted per unit volume due to excitations of level n' of ion Z in the ground state n is:

$$\frac{dP_L}{dV} = 2.7 \times 10^{-15} T^{-1/2} e^{-E_{nn'}/kT} f_{nn'} \overline{g_{nn'}}\, N_e N_Z \quad \text{erg cm}^{-3}\,\text{s}^{-1},$$

where

$E_{nn'}$ = energy of excitation,

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$f_{nn'}$ = oscillator strength for the transition,

$\overline{g_{nn'}}$ = mean Gaunt factor ≈ 0.2 for $kT/E_{nn'} < 1$.

In some cases, a line is produced by a transition to a state other than the ground state. In this case, the emitted power above is not equal to the power in the line and the branching ratio to the state of interest must be taken into account. For $1s$–$2p$ transitions in hydrogen and helium-like ions, this branching is not significant.

Radiative recombination radiation

$$\frac{dP_{RR,Z,n}}{dV\,dE} = \frac{2.8 \times 10^{-6} T^{-3/2} e^{(I_{Z-1,n}-E)/kT}}{n^3} N_e N_Z Z^4$$

$$\text{erg cm}^{-3}\,\text{s}^{-1}\,\text{erg}^{-1},$$

where

$E = W_i + I_{Z-1,n}$,

E = energy of emitted photon,

W_i = energy of free electron,

$I_{Z,n}$ = ionization energy of level n for ion Z.

(Adapted from Tucker, W. H. & Blumenthal, G. R. in *X-ray Astronomy*, R. Giacconi & H. Gursky, eds., D. Reidel Publishing Company, Dordrecht, 1974.)

Maxwell's equations (Gaussian units)

$$\nabla \cdot \mathbf{D} = 4\pi\rho, \quad \nabla \times \mathbf{H} = \frac{4\pi \mathbf{J}}{c} + \frac{1}{c}\frac{\partial D}{\partial t},$$

$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0.$$

Constitutive relations for an isotropic, permeable, conducting dielectric:

$$D = \varepsilon \mathbf{E}, \quad J = \sigma \mathbf{E}, \quad \mathbf{B} = \mu \mathbf{H}.$$

Macroscopic media:

$$\text{polarization:} \qquad \mathbf{P} = \frac{1}{4\pi}(\mathbf{D} - \mathbf{E}),$$

$$\text{magnetization:} \quad \mathbf{M} = \frac{1}{4\pi}(\mathbf{B} - \mathbf{H}).$$

Vector and scalar potentials:

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{E} = -\nabla\phi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}.$$

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For homogeneous, isotropic media, Maxwell's equations become:

$$\nabla^2\phi = \frac{\varepsilon\mu}{c^2}\frac{\partial^2\phi}{\partial t^2} - \frac{1}{c}\frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{A} + \frac{\varepsilon\mu}{c}\frac{\partial\phi}{\partial t}\right) - \frac{4\pi\rho}{\varepsilon}.$$

$$\nabla^2\mathbf{A} = \frac{\mu\varepsilon}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{A} + \nabla\left(\nabla\cdot\mathbf{A} + \frac{\varepsilon\mu}{c}\frac{\partial\phi}{\partial t}\right) - \frac{4\pi\mu}{c}\mathbf{J}.$$

Lorentz gauge:

$$\left(\nabla\cdot\mathbf{A} + \frac{\varepsilon\mu}{c}\frac{\partial\phi}{\partial t}\right) = 0.$$

Coulomb gauge:

$$\nabla\cdot\mathbf{A} = 0.$$

Conversion table for given amount of physical quantity

Physical quantity	Symbol	Rationalized MKS	Gaussian
Charge	q	1 coulomb	3×10^9 statcoulombs
Charge density	ρ	1 coul m^{-3}	3×10^3 statcoulombs cm^{-3}
Current	I	1 ampere	3×10^9 statamperes
Current density	J	1 amp m^{-2}	3×10^5 statamperes cm^{-2}
Electric field	E	1 volt m^{-1}	$1/3 \times 10^{-4}$ statvolt cm^{-1}
Potential	ϕ, V	1 volt	1/300 statvolt
Polarization	P	1 coul m^{-2}	3×10^5 statcoulombs cm^{-2}
Displacement	D	1 coul m^{-2}	$12\pi \times 10^5$ statvolt cm^{-1}
Conductivity	σ	1 mho m^{-1}	9×10^9 s^{-1}
Magnetic induction	B	1 weber m^{-2}	10^4 gauss
Magnetic field	H	1 ampere-turn m^{-1}	$4\pi \times 10^{-3}$ oersted
Magnetization	M	1 weber m^{-2}	$1/4\pi \times 10^4$ gauss

(Adapted from *Classical Electrodynamics*, Jackson, J. D., John Wiley and Sons, 1962.)

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Standard definitions in radiative transport theory

Quantity	Symbol	Units (cgs)
Specific intensity or radiance	I_ν	erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}
Brightness	$B_\nu = -I_\nu$	erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}
Flux density	$F_\nu = \int I_\nu \cos\theta \, d\Omega$	erg cm^{-2} s^{-1} Hz^{-1}
Mean intensity	$J_\nu = \frac{1}{4\pi} \int I_\nu \, d\Omega$	erg cm^{-2} s^{-1} Hz^{-1}
Radiation density	$u_\nu = \frac{1}{c} \int I_\nu \, d\Omega = \frac{4\pi}{c} J_\nu$	erg cm^{-3} Hz^{-1}
Emission coefficient	j_ν	erg cm^{-3} s^{-1} Hz^{-1} sr^{-1}
Emissivity	$\varepsilon_\nu = \frac{4\pi}{\rho} j_\nu$ (isotropic emission, ρ = density)	erg gm^{-1} s^{-1} Hz^{-1}
Linear absorption coefficient	$\alpha_\nu = n\sigma_\nu$ (n = number density, σ_ν = cross-section)	cm^{-1}
Mean free path	$l_\nu = \frac{1}{\alpha_\nu}$	cm
Optical depth	$\tau_\nu = \int \alpha_\nu \, ds$	dimensionless

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Maxwell's equations in various systems of units ($\varepsilon_0, \mu_0, \mathbf{D}, \mathbf{H}$, macroscopic Maxwell's equations, and Lorentz force equation in various systems of units)

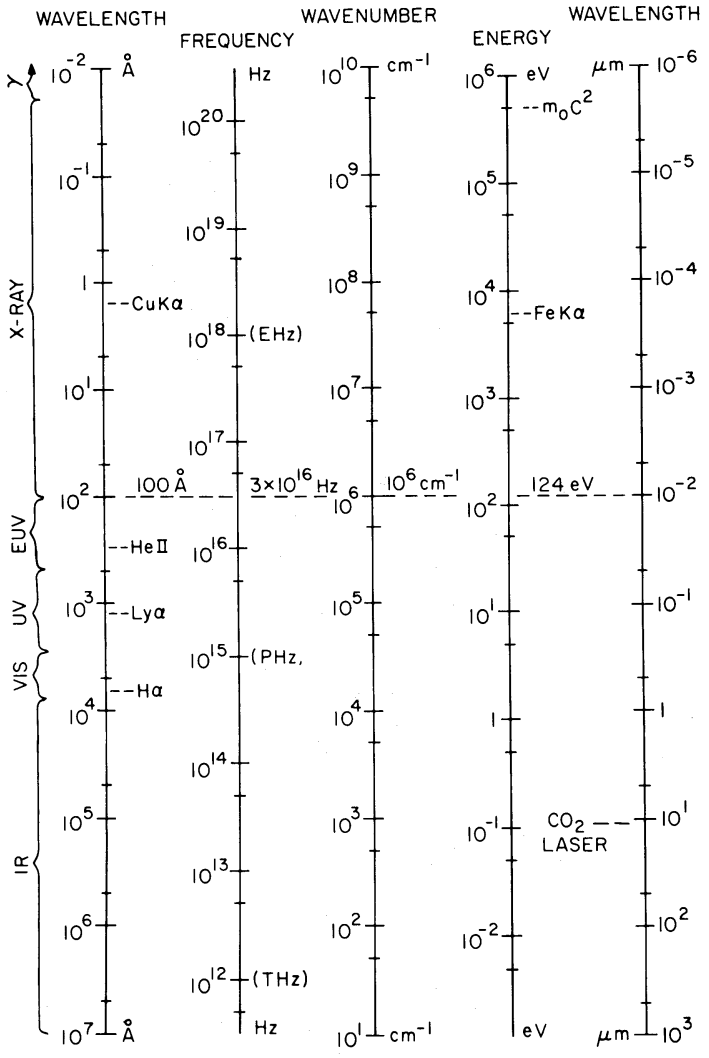
System	ε_0	μ_0	$\mathbf{D}, \mathbf{H}$	Macroscopic Maxwell's equations				Lorentz force per unit charge
Electrostatic (esu)	1	c^{-2}	$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}$ $\mathbf{H} = c^2\mathbf{B} - 4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D} = 4\pi\rho$	$\nabla\times\mathbf{H} = 4\pi\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$	$\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$	$\nabla\cdot\mathbf{B} = 0$	$\mathbf{E} + v\times\mathbf{B}$
Electro-magnetic (emu)	c^{-2}	1	$\mathbf{D} = (1/c^2)\mathbf{E} + 4\pi\mathbf{P}$ $\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D} = 4\pi\rho$	$\nabla\times\mathbf{H} = 4\pi\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$	$\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$	$\nabla\cdot\mathbf{B} = 0$	$\mathbf{E} + v\times\mathbf{B}$
Gaussian	1	1	$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}$ $\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D} = 4\pi\rho$	$\nabla\times\mathbf{H} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial\mathbf{D}}{\partial t}$	$\nabla\times\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0$	$\nabla\cdot\mathbf{B} = 0$	$\mathbf{E} + \frac{v}{c}\times\mathbf{B}$
Heaviside–Lorentz	1	1	$\mathbf{D} = \mathbf{E} + \mathbf{P}$ $\mathbf{H} = \mathbf{B} - \mathbf{M}$	$\nabla\cdot\mathbf{D} = \rho$	$\nabla\times\mathbf{H} = \frac{1}{c}\left(\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}\right)$	$\nabla\times\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0$	$\nabla\cdot\mathbf{B} = 0$	$\mathbf{E} + \frac{v}{c}\times\mathbf{B}$
Rationalized mks	$\frac{10^7}{4\pi c^2}$	$4\pi\times 10^{-7}$	$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$ $\mathbf{H} = (1/\mu_0)\mathbf{B} - \mathbf{M}$	$\nabla\cdot\mathbf{D} = \rho$	$\nabla\times\mathbf{H} = \mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$	$\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$	$\nabla\cdot\mathbf{B} = 0$	$\mathbf{E} + v\times\mathbf{B}$

(Adapted from Jackson, J. D., *Classical Electrodynamics*, John Wiley and Sons, 1962.)

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Spectrum nomogram

Electromagnetic spectrum nomogram.



Bibliography

Radiation Processes in Astrophysics, Tucker, W., The MIT Press, 1975.

Radiative Processes in Astrophysics, Rybicki, G. B. & Lightman, A. P., John Wiley and Sons, 1979.

Classical Electrodynamics, Jackson, J. D., John Wiley and Sons, 1962.

Astrophysical Formulae, Lang, K. R., Springer-Verlag, 1980.

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