# Chapter 12

# *Electromagnetic radiation*


| | page |
|---|---|
| Blackbody radiation | 268 |
| *Planck functions* | 268 |
| *Radiation curves* | 269 |
| Synchrotron radiation | 270 |
| *Single electron in a magnetic field* | 270 |
| *General distribution of electrons* | 271 |
| *Power law distribution of electrons* | 271 |
| Compton scattering | 272 |
| *Compton shift* | 272 |
| *Energy of scattered photon* | 272 |
| *Energy of struck electrons* | 272 |
| *Relation between the scattering angles* | 272 |
| *Klein–Nishina cross-section* | 272 |
| *Klein–Nishina differential cross-sections* | 273 |
| Inverse Compton scattering | 274 |
| *Total energy loss rate* | 274 |
| *Spectra* | 275 |
| Hot plasma emission | 276 |
| *Bremsstrahlung from a hot plasma* | 276 |
| *Non-thermal bremsstrahlung* | 276 |
| *X-ray line emission from a hot plasma* | 276 |
| *Radiative recombination radiation* | 277 |
| Maxwell's equations | 277 |
| Conversion table | 278 |
| Standard definitions in radiative transport theory | 279 |
| Maxwell's equations in various systems of units | 280 |
| Spectrum nomogram | 281 |
| Bibliography | 281 |


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## Blackbody radiation (cgs units)

***Planck functions*** (brightness of a blackbody)

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

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

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

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

*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*

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

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

*Wien displacement law*

*Maximizing $B_\nu$:*

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

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

*Maximizing $B_\lambda$:*

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

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

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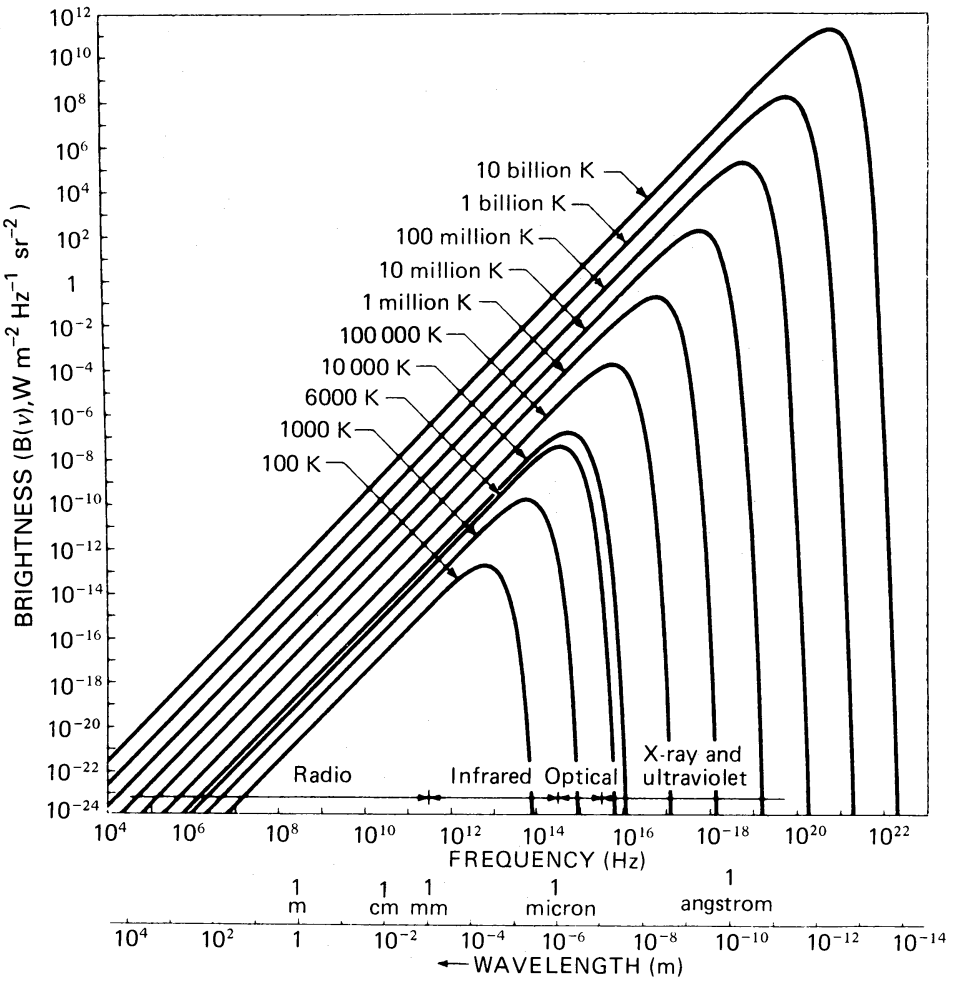
*Mean photon energy*

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

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,
$\alpha$ = 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:

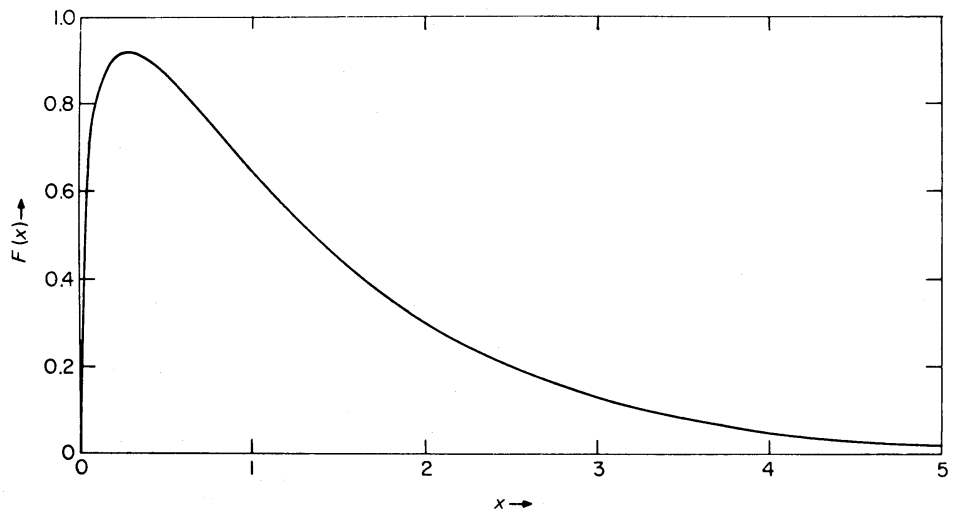
$$P(\nu) = 2.3 \times 10^{-22} B \sin\alpha F(\nu/\nu_c) \quad \text{erg s}^{-1}\,\text{Hz}^{-1} \quad (\alpha >> 1/\gamma).$$

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

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

$K_{5/3}(\xi)$ 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,

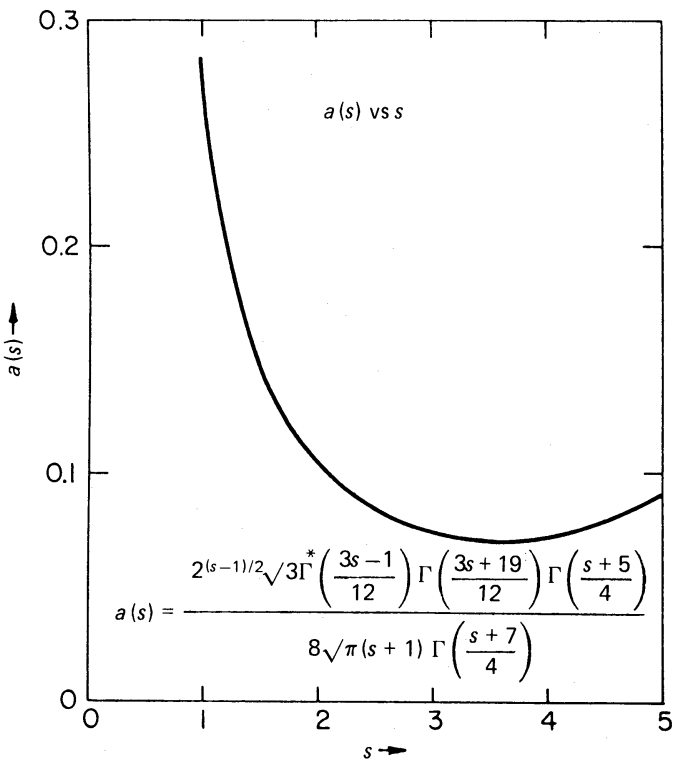
where $n(\gamma,\alpha)\,d\gamma\,d\Omega_\alpha$ = density of electrons with Lorentz factor between $\gamma$ and $\gamma + d\gamma$ and pitch angle between $\alpha$ and $\alpha + d\alpha$; $d\Omega_\alpha = 2\pi \sin\alpha\, d\alpha$; $P(\nu)$ = single electron spectrum.

***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: $\Gamma(x)$ is the gamma function.

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

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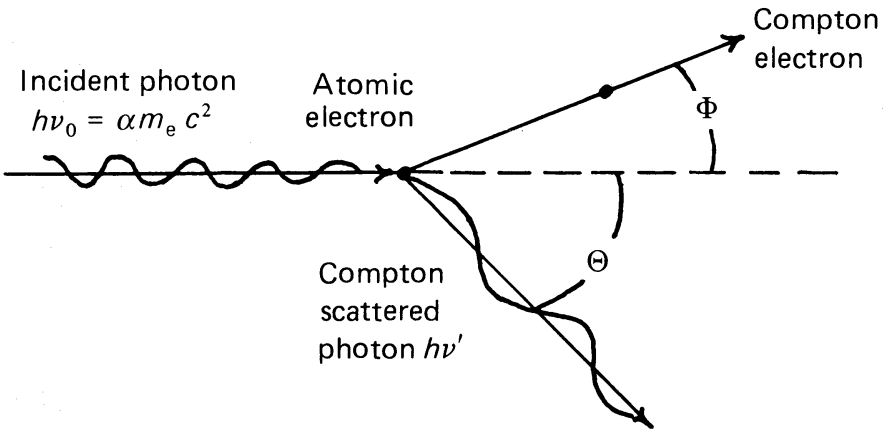
**Compton scattering** (cgs units)




***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, $\phi$ and $\theta$***

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

***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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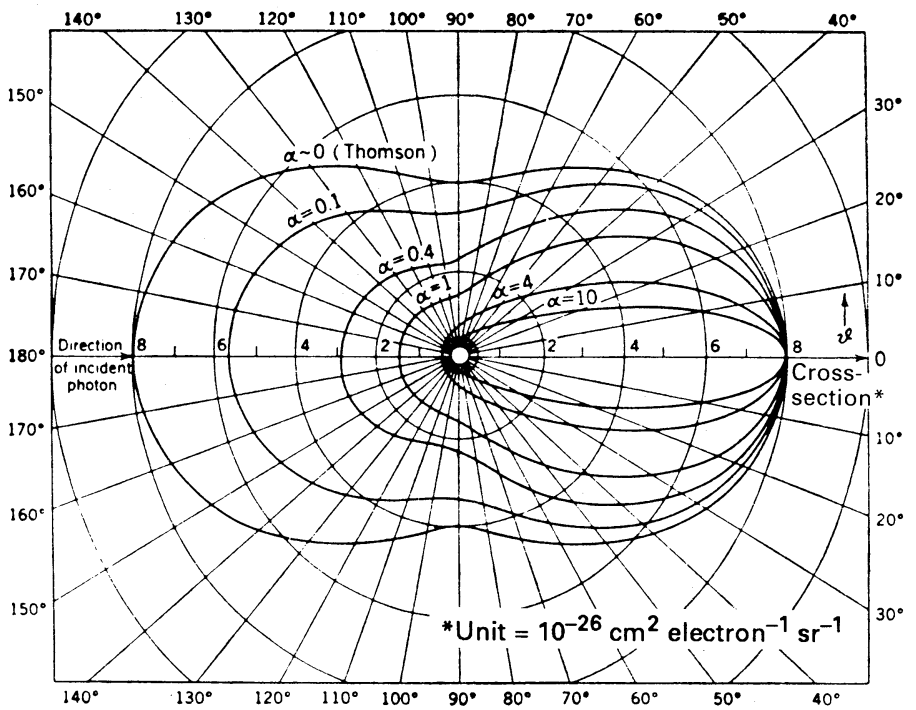
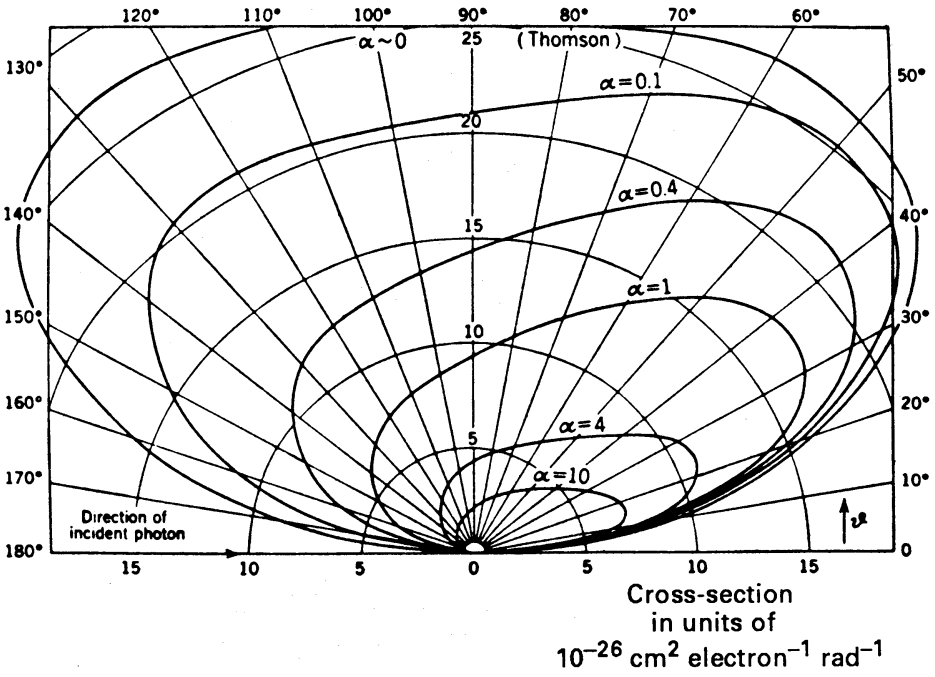
### *Klein–Nishina differential cross-sections*

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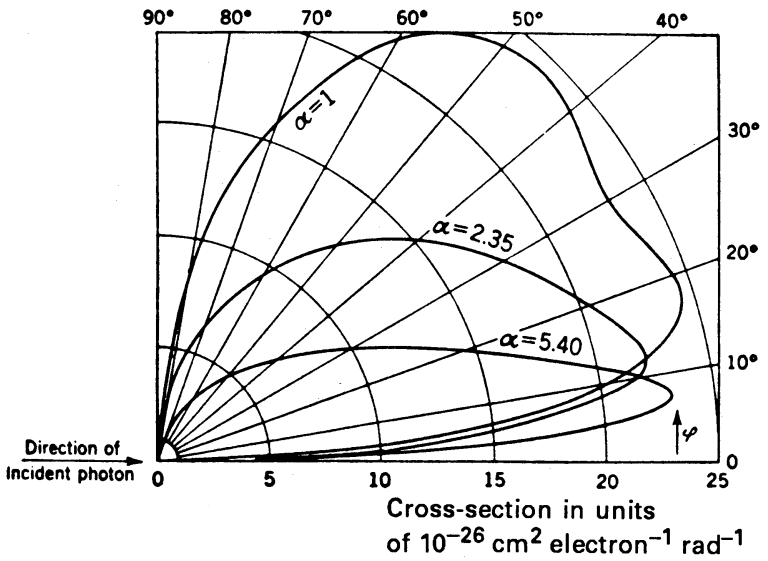
***Klein–Nishina differential cross-sections*** (*cont.*)

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 $\gamma$ 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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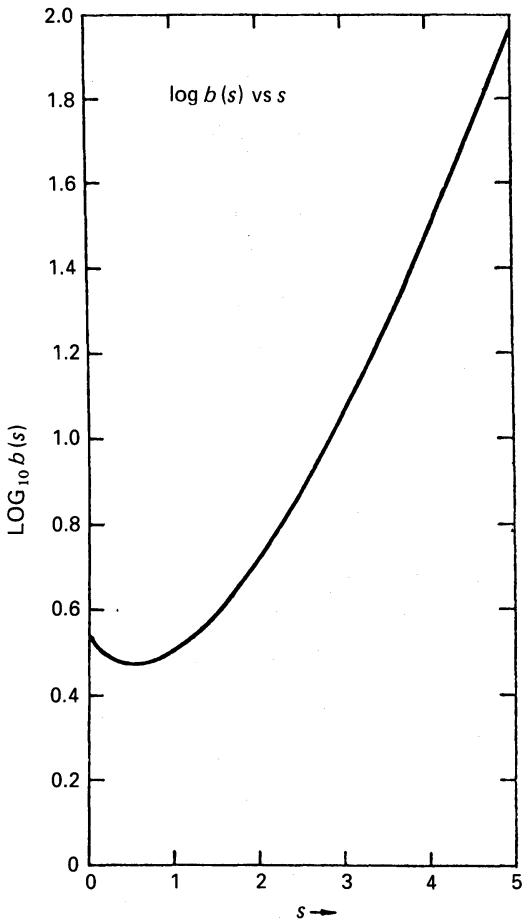
***Spectra***

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 $\gamma$ 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.

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

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

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 $\approx 0.2$ 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 | $3 \times 10^9$ statcoulombs |
| Charge density | $\rho$ | 1 coul $m^{-3}$ | $3 \times 10^3$ statcoulombs $cm^{-3}$ |
| Current | $I$ | 1 ampere | $3 \times 10^9$ statamperes |
| Current density | $J$ | 1 amp $m^{-2}$ | $3 \times 10^5$ statamperes $cm^{-2}$ |
| Electric field | $E$ | 1 volt $m^{-1}$ | $1/3 \times 10^{-4}$ statvolt $cm^{-1}$ |
| Potential | $\phi, V$ | 1 volt | 1/300 statvolt |
| Polarization | $P$ | 1 coul $m^{-2}$ | $3 \times 10^5$ statcoulombs $cm^{-2}$ |
| Displacement | $D$ | 1 coul $m^{-2}$ | $12\pi \times 10^5$ statvolt $cm^{-1}$ |
| Conductivity | $\sigma$ | 1 mho $m^{-1}$ | $9 \times 10^9$ $s^{-1}$ |
| 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 | $I_\nu$ | 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 | $j_\nu$ | erg cm$^{-3}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ |
| Emissivity | $\varepsilon_\nu = \frac{4\pi}{\rho} j_\nu$ (isotropic emission, $\rho$ = density) | erg gm$^{-1}$ s$^{-1}$ Hz$^{-1}$ |
| Linear absorption coefficient | $\alpha_\nu = n\sigma_\nu$ ($n$ = number density, $\sigma_\nu$ = 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 | $\varepsilon_0$ | $\mu_0$ | $\mathbf{D}, \mathbf{H}$ | Macroscopic Maxwell's equations | | | | Lorentz force per unit charge |
|---|---|---|---|---|---|---|---|---|
| Electrostatic (esu) | 1 | $c^{-2}$ | $\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}$<br>$\mathbf{H} = c^2\mathbf{B} - 4\pi\mathbf{M}$ | $\nabla\cdot\mathbf{D} = 4\pi\rho$ | $\nabla\times\mathbf{H} = 4\pi\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$ | $\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$ | $\nabla\cdot\mathbf{B} = 0$ | $\mathbf{E} + v\times\mathbf{B}$ |
| Electro-magnetic (emu) | $c^{-2}$ | 1 | $\mathbf{D} = (1/c^2)\mathbf{E} + 4\pi\mathbf{P}$<br>$\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$ | $\nabla\cdot\mathbf{D} = 4\pi\rho$ | $\nabla\times\mathbf{H} = 4\pi\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$ | $\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$ | $\nabla\cdot\mathbf{B} = 0$ | $\mathbf{E} + v\times\mathbf{B}$ |
| Gaussian | 1 | 1 | $\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}$<br>$\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$ | $\nabla\cdot\mathbf{D} = 4\pi\rho$ | $\nabla\times\mathbf{H} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial\mathbf{D}}{\partial t}$ | $\nabla\times\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0$ | $\nabla\cdot\mathbf{B} = 0$ | $\mathbf{E} + \frac{v}{c}\times\mathbf{B}$ |
| Heaviside–Lorentz | 1 | 1 | $\mathbf{D} = \mathbf{E} + \mathbf{P}$<br>$\mathbf{H} = \mathbf{B} - \mathbf{M}$ | $\nabla\cdot\mathbf{D} = \rho$ | $\nabla\times\mathbf{H} = \frac{1}{c}\left(\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}\right)$ | $\nabla\times\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0$ | $\nabla\cdot\mathbf{B} = 0$ | $\mathbf{E} + \frac{v}{c}\times\mathbf{B}$ |
| Rationalized mks | $\frac{10^7}{4\pi c^2}$ | $4\pi\times 10^{-7}$ | $\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$<br>$\mathbf{H} = (1/\mu_0)\mathbf{B} - \mathbf{M}$ | $\nabla\cdot\mathbf{D} = \rho$ | $\nabla\times\mathbf{H} = \mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$ | $\nabla\times\mathbf{E} + \frac{\partial\mathbf{B}}{\partial t} = 0$ | $\nabla\cdot\mathbf{B} = 0$ | $\mathbf{E} + v\times\mathbf{B}$ |

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

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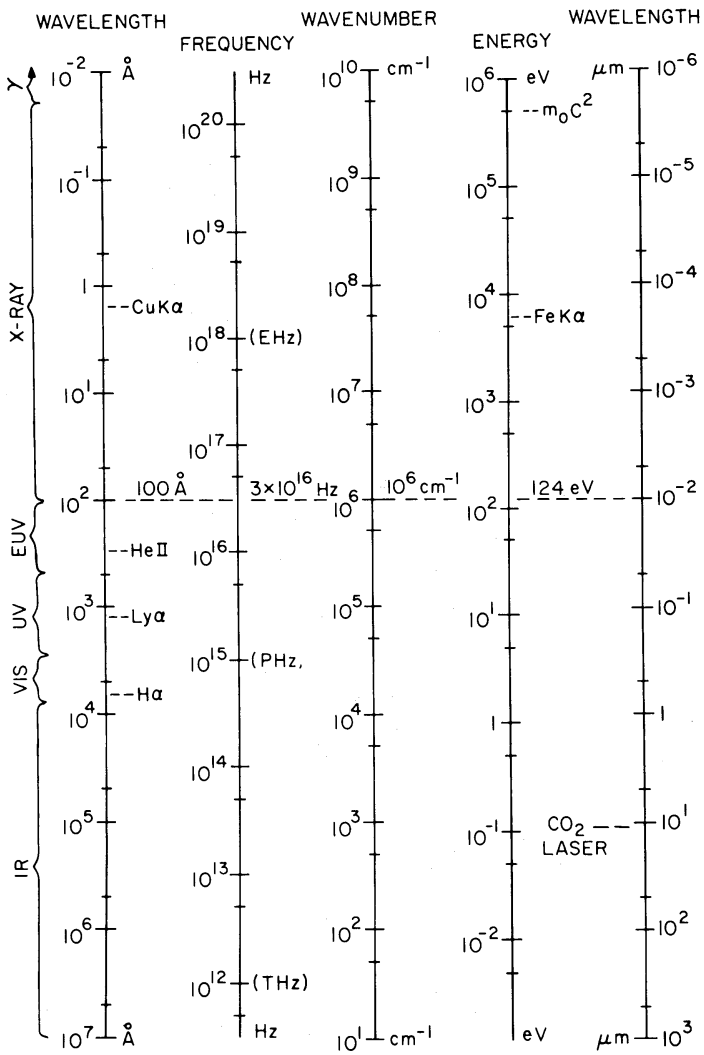
## Spectrum nomogram

Electromagnetic spectrum nomogram.

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