

Appendix I

Constants

| Constant | Symbol | Value |
|---|--------------|---|
| Universal constants | | |
| Speed of light in vacuum | c | $2.9979 \times 10^8 \text{ m s}^{-1}$ |
| Universal gravitational constant | G | $6.674 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ $6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ |
| Planck constant | h | $6.6261 \times 10^{-34} \text{ J s}$ |
| Electric constant | ϵ_0 | $8.8542 \times 10^{-12} \text{ F m}^{-1}$ |
| Magnetic constant | μ_0 | $1.2566 \times 10^{-6} \text{ N A}^{-2}$ |
| Thermal radiation | | |
| Boltzmann constant | k | $1.38065 \times 10^{-23} \text{ J K}^{-1}$ |
| Stefan-Boltzmann constant | σ | $5.6704 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4}$ |
| Radiation density constant | a | $7.5657 \times 10^{-16} \text{ J m}^{-3} \text{ K}^{-4}$ |
| Wien wavelength displacement law constant | b | $2.8978 \times 10^{-3} \text{ m K}$ |
| Atomic and nuclear | | |
| Electron mass | m_e | $9.1094 \times 10^{-31} \text{ kg}$ |
| Elementary charge | e | $1.6022 \times 10^{-19} \text{ C}$ |
| Classical electron radius | r_e | $2.8179 \times 10^{-15} \text{ m}$ |
| Thomson scattering cross section | σ_T | $6.65246 \times 10^{-29} \text{ m}^2$ |
| Atomic mass unit | $m_u = u$ | $1.660539 \times 10^{-27} \text{ kg}$ |
| Proton mass | m_p | $1.6726 \times 10^{-27} \text{ kg}$ |
| Neutron mass | m_n | $1.6749 \times 10^{-27} \text{ kg}$ |
| Alpha particle mass | m_α | $6.644656 \times 10^{-27} \text{ kg}$ |
| Bohr radius | a_0 | $5.2918 \times 10^{-11} \text{ m}$ |
| Rydberg constant | R_∞ | $10,973,731.5685 \text{ m}^{-1}$ |
| Sun | | |
| Mass of the Sun | M_\odot | $1.989 \times 10^{30} \text{ kg}$ |
| Luminosity of Sun | L_\odot | $3.828 \times 10^{26} \text{ J s}^{-1}$ |
| Radius of Sun | R_\odot | $6.955 \times 10^8 \text{ m}$ |
| Expanding universe | | |
| Hubble constant | H_0 | $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ |
| Age of expanding Universe | t_0 | $13.7 \times 10^9 \text{ years}$ |

(continued)

(continued)

| Constant | Symbol | Value |
|--|--------------------|-----------------------------------|
| Cosmic microwave background radiation | | |
| Temperature | T_{CMB} | 2.725 K |
| Photon density | N_{CMB} | $4.10 \times 10^8 \text{ m}^{-3}$ |
| Anisotropy | $\Delta T/T_{CMB}$ | 1.1×10^{-5} |

The physical constants are accurate to the fourth decimal place. For greater accuracy with the latest values consult <http://physics.nist.gov/cuu/constants/index.html>

Appendix II

Units

| Unit | Symbol | Value |
|--|---------------|--|
| Distance and length | | |
| Ångström | Å | 10^{-10} m |
| Meter | m | 1 km = 10^3 m = 0.621371 mile 1 mile = 1.60934 km |
| Mean Earth-Sun distance | AU | 1.49598×10^{11} m |
| Light-year | ly | 9.460528×10^{15} m = 63,239.67 AU |
| Parsec | pc | 3.08568×10^{16} m = 3.26164 light-years = 206,265 AU |
| Megaparsec | Mpc | 10^6 pc |
| Angle | | |
| Degree | ° | $60' = 3600''$ $1^\circ = 0.0174532925$ radians $1'' = 4.8481368 \times 10^{-6}$ radians |
| (The symbol ' denotes minutes of arc, the symbol '' designates seconds of arc) | | |
| Radian | rad | $2.06265 \times 10^5 ''$ $57.2957795^\circ = 360^\circ / (2\pi)$ |
| Pi | π | 3.141592654 |
| Time | | |
| Solar day | day | 24 h = 86,400 s |
| Sidereal day | sidereal day | 23 h 56 m 04.09 s = 23.9344696 h |
| Year | tropical year | 365.25 solar days = 3.15576×10^7 s |
| Energy, power, force, pressure | | |
| Joule | J | 10^7 erg |
| Electron-volt | ev | 1.6018×10^{-19} J |
| Power | Watt | J s^{-1} |
| Force | N | kg m s^{-2} |
| Pressure | Pa | N m^{-2} |

(continued)

(continued)

| Unit | Symbol | Value |
|--------------------|-------------|--|
| Mass | | |
| Kilogram | kg | 1,000 g, 1 metric ton = 10^3 kg |
| Solar units | | |
| Mass of the Sun | M_{\odot} | 1.989×10^{30} kg |
| Luminosity of Sun | L_{\odot} | 3.828×10^{26} J s ⁻¹ |
| Radius of Sun | R_{\odot} | 6.955×10^8 m |

Appendix III

Fundamental Equations

Angular resolution, θ_r , of a telescope of diameter, D_T , at a wavelength, λ :

$$\theta_r = \frac{\lambda}{D_T} \text{ radians} \quad (\text{A-1})$$

where 1 radian = 2.06265×10^5 seconds of arc = 2.06265×10^5 ''.

Angular source extent, θ_{size} , of a celestial source of radius, R , located at a distance, D :

$$\theta_{size} = \frac{2R}{D} \text{ radians}, \quad (\text{A-2})$$

where 1 radian = 2.06265×10^5 seconds of arc = 2.06265×10^5 ''.

Wavelength, λ , **frequency**, ν , and **speed of light**, c :

$$\lambda \times \nu = c, \quad (\text{A-3})$$

where the speed of light $c = 2.9979 \times 10^8$ m s⁻¹.

Photon energy, E , of radiation at frequency ν :

$$E = h\nu \quad (\text{A-4})$$

where the Planck constant $h = 6.6261 \times 10^{-34}$ J s.

Stefan-Boltzmann law for luminosity, L , of thermal radiator with effective temperature T_{eff} and radius R :

$$L = 4\pi\sigma R^2 T_{eff}^4 \quad (\text{A-5})$$

where $\pi = 3.14159$ and the Stefan-Boltzmann constant $\sigma = 5.6704 \times 10^{-8}$ J s⁻¹ m⁻² K⁻⁴.

Apparent magnitude, absolute magnitude, and luminosity for a star. Any apparent magnitude, m , can be converted to absolute magnitude, M , through the simple formula:

$$\text{absolute magnitude} = M = m + 5 - 5 \log D, \quad (\text{A-6})$$

where D is the distance in parsecs, and 1 parsec = 3.26164 light-years = 3.08568×10^{16} m. The absolute magnitude can be converted into a luminosity, L , using:

$$\log \left(\frac{L}{L_{\odot}} \right) = 0.4(M_{\odot} - M), \quad (\text{A-7})$$

or

$$L = 10^{0.4(M_{\odot} - M)} L_{\odot}, \quad (\text{A-8})$$

where the absolute magnitude of the Sun in the visual range of wavelengths, where it is most intense, is $M_{\odot} = +4.83$ and the absolute luminosity of the Sun is $L_{\odot} = 3.828 \times 10^{26}$ J s⁻¹. Notice that the symbol M_{\odot} is used to denote both the absolute magnitude of the Sun, which is used here, and the mass of the Sun, used in other equations. The Sun has an apparent magnitude of $m_{\odot} = -26.74$.

Wien displacement law for wavelength λ_{max} of maximum intensity for a thermal radiator at temperature T :

$$\lambda_{\text{max}} = \frac{0.002898}{T} \text{ meters.} \quad (\text{A-9})$$

Radiant flux, f , or apparent brightness, of an object of luminosity L at distance D :

$$f = \frac{L}{4\pi D^2}. \quad (\text{A-10})$$

Gravitational force, F_G , between two masses, M_1 and M_2 separated by a distance D between their centers:

$$F_G = \frac{GM_1M_2}{D^2}, \quad (\text{A-11})$$

where the universal gravitational constant $G = 6.674 \times 10^{-11}$ m³ kg⁻¹ s⁻².

Kepler's third law for the orbital period P of a binary system of mass M_1 and M_2 separated by distance a :

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \quad (\text{A-12})$$

where the universal gravitational constant $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.

Jeans mass, M_J , for a spherical gas cloud of radius, R , and temperature, T :

$$M_J = \frac{3kT}{Gm}R, \quad (\text{A-13})$$

where the Boltzmann constant $k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$, the universal gravitational constant $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, and m is the gas particle mass. Gravitational collapse occurs if the cloud mass, M , is greater than the Jeans mass, M_J .

Escape velocity, V_{esc} , at a distance R from a mass M :

$$V_{esc} = \left(\frac{2GM}{R} \right)^{1/2}, \quad (\text{A-14})$$

where the universal gravitational constant $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.

Doppler effect for a change $\Delta\lambda$ in the wavelength λ due to a radial velocity V_r of a source moving away from observer:

$$\frac{\Delta\lambda}{\lambda_{emitted}} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} = \frac{V_r}{c} \quad \text{for } V_r \ll c, \quad (\text{A-15})$$

where the speed of light $c = 2.9979 \times 10^8 \text{ m s}^{-1}$.

Parallax the annual parallax π_A , of a star at distance, D , is:

$$\pi_A = \text{AU}/D \text{ radians}, \quad (\text{A-16})$$

where $1 \text{ AU} = 1.49598 \times 10^{11} \text{ m}$ and $1 \text{ radian} = 2.06265 \times 10^5 \text{ s of arc}$. When the parallax is given in units of seconds of arc, then the distance, D , is given by:

$$D = \frac{1}{\pi_A} \text{ parsecs}, \quad (\text{A-17})$$

where $1 \text{ parsec} = 3.26164 \text{ light years} = 206,265.8 \text{ AU}$.

Gravitational potential energy of a mass, M , with radius, R :

$$\text{Gravitational potential energy} = \frac{GM^2}{R}, \quad (\text{A-18})$$

where the universal gravitational constant $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.

Kinetic energy of mass, m , moving at velocity, V :

$$\text{Kinetic energy} = \frac{1}{2}mV^2. \quad (\text{A-19})$$

Thermal energy at temperature, T :

$$\text{Thermal energy} = \frac{3}{2}kT, \quad (\text{A-20})$$

where the Boltzmann constant $k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$.

Thermal velocity, $V_{thermal}$, of a particle of mass, m , at temperature, T :

$$V_{thermal} = \sqrt{\frac{3kT}{m}} = \left[\frac{3kT}{m} \right]^{1/2}, \quad (\text{A-21})$$

where the Boltzmann constant $k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$.

Gas pressure, P_G , of particles of number density, N , and temperature T :

$$P_G = NkT, \quad (\text{A-22})$$

where the Boltzmann constant $k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$.

Radiation pressure, P_r , for a temperature T :

$$P_r = \frac{aT^4}{3} \quad (\text{A-23})$$

where the radiation constant $a = 7.5657 \times 10^{-16} \text{ J m}^{-3} \text{ K}^{-4}$.

Magnetic pressure, P_B , of a magnetic field of strength, B :

$$P_B = \frac{B^2}{2\mu_0}, \quad (\text{A-24})$$

where the magnetic constant $\mu_0 = 1.2566 \times 10^{-6} \text{ N A}^{-2}$.

Energy radiated, ΔE , by a mass loss, Δm , during nuclear reactions:

$$\Delta E = \Delta m c^2, \quad (\text{A-25})$$

where the speed of light $c = 2.9979 \times 10^8 \text{ m s}^{-1}$.

Schwarzschild radius, R_{sch} , of a mass, M , of radius R :

$$R_{sch} = \frac{2GM}{c^2} = 2.95 \times 10^3 \left(\frac{M}{M_\odot} \right) \text{m}, \quad (\text{A-26})$$

where the universal gravitational constant $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ and the Sun's mass $M_\odot = 1.989 \times 10^{30} \text{ kg}$.

Hubble law for the recession velocity V_r of a galaxy at a distance D :

$$V_r = H_0 \times D, \quad (\text{A-27})$$

where the Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $1 \text{ Mpc} = 3.08568 \times 10^{22} \text{ m}$.

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