

GENERAL QUALIFYING EXAM SOLUTIONS: APPENDIX

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1 Appendix

1.1 Acronyms

AGN: active galactic nuclei
AU: astronomical unit
BAOs: baryonic acoustic oscillations
BB: Big Bang or blackbody
BCD: blue compact dwarf
BBN: Big Bang nucleosynthesis
bf: bound-free
BH: black hole
CCD: charged couple device
CCD: colour-colour diagram
CCM: Cardelli-Clayton-Mathis
CIB: Cosmic Infrared Background
CMB: Cosmic Microwave Background
CMD: colour-magnitude diagram
CNB: Cosmic Neutrino Background
COBE: COsmic Background Explorer
CDM: cold dark matter
cE: compact elliptical
CIB: cosmic infrared background
CMB: cosmic microwave background
CR: cosmic ray
CRB: cosmic radio background
CGB: cosmic gamma-ray background
CUVOB: cosmic ultraviolet/optical background
CXB: cosmic x-ray background
DDA: discrete dipole approximation
DE: dark energy
dE: dwarf elliptical
DIBS: diffuse interstellar bands
DM: dark matter
DM: distance modulus
dSph: dwarf spheroidal
E: elliptical
EM: electromagnetic
EOM: equation of motion
EoR: epoch of reionization
EOS: equation of state
ERE: extended red emission
ff: free-free
FIR: far infrared
GC: galactic center
GC: globular cluster
gE: giant elliptical
GMC: giant molecular cloud
GP: Gunn-Peterson
GUT: grand unified theory
HRD: Hertzsprung-Russel diagram
HST: Hubble Space Telescope
ICM: intracluster medium
IGM: intergalactic medium
IMF: initial mass function
IR: infrared
Irr: irregular
ISM: interstellar medium
LAE: Lyman-alpha emitter
LBG: Lyman break galaxy
LG: Local Group

LMC: Large Magellanic Cloud
LTE: local thermodynamic equilibrium
MACHO: massive compact halo objects
MMR: mass-magnitude relation
MW: Milky Way
MWG: Milky Way Galaxy
NLTE: non-local thermodynamic equilibrium
NS: neutron star
ONC: Orion Nebula cluster
PAH: polycyclic aromatic hydrocarbon
pc: parsec
PDMF: present-day mass function
PDF: probability distribution function
PGM: pre-galactic medium
PL: period-luminosity
PSF point-spread function
QFT: quantum field theory
QSO: quasi-stellar object
RJ: Rayleigh-Jeans
RT: radiative transfer
RTE: radiative transfer equation
S: spiral
SB: barred spiral
SDSS: Sloan Digital Sky Survey
SED: spectral energy distribution
SF: star formation
SFR: star formation rate
SFRD: star formation rate density
SMC: Small Magellanic Cloud
SMBH: supermassive black hole
SMG: sub-millimeter galaxy
S/N: signal-to-noise
SNR: signal-to-noise ratio
STMD: spectral type - magnitude diagram
SZ: Sunyaev-Zeldovich
SZE: Sunyaev-Zeldovich effect
TE: thermal equilibrium
TE: thermodynamic equilibrium
VLBI: Very Long Baseline Interferometry
WD: white dwarf
WIMP: weakly interacting massive particle
 Λ CDM: Λ cold dark matter
2dFGRS: 2 degree Field Galactic Redshift Survey

1.2 Variables

Absolute magnitude: M [mag]
Absorption coefficient: α_ν [cm^{-1}]
Albedo: ω [dimensionless]
Ampere: A [unit]
Angström: Å [unit]
Angular diameter distance: d_A [pc]
Angular momentum per unit mass: \vec{L} [$\text{m}^2 \text{s}^{-1} \text{kg}^{-1}$]
Angular size: θ [rad]
Apocenter: r_2 [AU]
Apparent magnitude: m [mag]
Attenuation: see *extinction*
Auxiliary magnetic field: \vec{H} [A m^{-1}]
Azimuthal angle: ψ [rad]
Azimuthal period: T_ψ [yr]
Baryon fraction: f_b [dimensionless]
Baryon temperature: T_b [K]
Binding energy of deuterium: E_D [MeV]
Binding energy of helium: E_{He} [MeV]
Binding energy of hydrogen: E_{H} [MeV]
Black hole mass: M_\bullet [M_\odot]
Black hole radius of influence: r_{BH} [pc]
Black hole radius of influence (angular): r_{BH} [arcsec]
Blackbody function: $B_\nu(T)$ [$\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$]
Bohr magneton: μ_B [erg G^{-1}]
Boltzmann constant: k_B [$\text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$]
Bonnor-Ebert mass: M_{BE} [M_\odot]
Brightness temperature: T_b [K]
Brightness temperature of radio source: T_r [K]
Chandrasekhar mass: M_C [M_\odot]
Charge: q [C]
CMB power spectrum amplitude: C_ℓ [μK^2]
CMB temperature: T_{CMB} [K]
CMB temperature fluctuations: $\Delta T/T$ [dimensionless]
CNB temperature: T_{CNB} [K]
Collisional coupling for species i : x_c^i [dimensionless]
Collisional excitation rate: C_{10} [s^{-1}]
Colour excess ($B - V$): $E(B - V)$ [mag]
Comoving sound horizon: $r_{\text{H,com}}$ [Mpc]
Compton y -parameter: y [dimensionless]
Correlation function: $C(\theta)$ [dimensionless]
Cosmological constant: Λ [m^{-2}]
Coulomb: C [unit]
Coupling coefficient of collisions: x_c [dimensionless]
Coupling coefficient of Ly α scattering: x_α [dimensionless]
Coupling coefficient (total): x_{tot} [dimensionless]
Critical density: ρ_c [g cm^{-3}]
Critical density: ρ_{crit} [g cm^{-3}]
Cross section: σ [cm^2]
Cross section (absorption): C_{abs} [cm^2]
Cross section (extinction): C_{ext} [cm^2]
Cross section (radiation pressure): C_{pr} [cm^2]
Cross section (scattering): C_{sca} [cm^2]
Crossing timescale: t_{cross} [yr]
Curvature term: $S_\kappa(r)$ [Mpc]
Dark energy density: ρ_Λ [g cm^{-3}]
Deceleration parameter: q_0 [dimensionless]
Degeneracy: see *statistical weight*
Density contrast: $\delta(\mathbf{x}, t)$ [dimensionless]
Density of baryons: ρ_b [m^{-3}]

Density of dark energy: ρ_Λ [kg m^{-3}]
 Density of neutrinos: ρ_ν [m^{-3}]
 Density of neutrons: ρ_b [m^{-3}]
 Density of protons: ρ_b [m^{-3}]
 Density of vacuum: ρ_{vac} [eV m^{-3}]
 Density parameter: Ω_i [dimensionless]
 Density parameter of baryonic matter: Ω_b [dimensionless]
 Density parameter of curvature: Ω_κ [dimensionless]
 Density parameter of dark energy: Ω_Λ [dimensionless]
 Density parameter of dark matter: Ω_c [dimensionless]
 Density parameter of matter: Ω_m [dimensionless]
 Density parameter of neutrinos: Ω_ν [dimensionless]
 Density parameter of radiation: Ω_r [dimensionless]
 Density perturbation field: $\delta(\mathbf{x}, t)$ [dimensionless]
 Density PDF: $p(\rho)$ [???]
 Deuterium: D [element]
 Disk scale length: h_R [Mpc]
 Distance: d [m]
 Distance modulus: $m - M$ [mag]
 Dust abundance (scaled to Solar neighborhood value): Z'_d [???]
 Dust optical depth: τ_d [dimensionless]
 Eccentricity: e [dimensionless]
 Effective radius of dust grain: a_{eff} [μm]
 Efficiency factor (absorption): Q_{abs} [cm^{-2}]
 Efficiency factor (extinction): Q_{ext} [cm^{-2}]
 Efficiency factor (scattering): Q_{sca} [cm^{-2}]
 Effective number of neutrino families: N_{eff} [dimensionless]
 Effective radius: R_e [Mpc]
 Einstein A coefficient (spontaneous emission): A_{10} [s^{-1}]
 Einstein B coefficient (spontaneous absorption): B_{01} [s^{-1}]
 Einstein B coefficient (stimulated emission): B_{10} [s^{-1}]
 Electric field: $\vec{E} = \text{N C}^{-1}$
 Electric polarizability: $\alpha = \text{C m}^2 \text{V}^{-1}$
 Electrical conductivity: $\sigma = \text{S m}^{-1}$
 Electron: e^- [particle]
 Electronvolt: eV [unit]
 Electron optical depth: τ_e [dimensionless]
 Electroweak age: t_{ew} [s]
 Electroweak energy: E_{ew} [TeV]
 Electroweak temperature: T_{ew} [K]
 Electron radius (classical): $r_{e,0}$ [cm]
 Elliptical D_n : D_n [pc]
 Ellipticity: ϵ [dimensionless]
 Emission coefficient: j_ν [cm^{-1}]
 Energy: E [eV or J]
 Energy density: *see density parameter*
 Energy of CMB photons: E_{CMB} [eV]
 Energy of photons: E_γ [eV]
 Escape velocity: v_{esc} [km s^{-1}]
 Excitation temperature: T_{ex} [K]
 Extinction: A_ν or A_λ [mag]
 Extinction coefficient: *see extinction*
 Extinction coefficient for the MWG: $A_{V,\text{MWG}}$ [mag]
 Farad: F [unit]
 Flux: F [$\text{erg s}^{-1} \text{cm}^{-2}$]
 Flux (spectral): F_ν [$\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$]
 Frequency: ν [Hz]
 Fourier transform: $P(k)$ [function]
 FUV intensity: χ_{FUV} [???]
 Gas surface mass density: Σ_{gas} $\text{M}_\odot \text{pc}^{-2}$
 Gas temperature: T_g [K]

Gravitational acceleration (norm): g [m s^{-2}]
Gravitational acceleration (vector): \vec{g} [m s^{-2}]
Gravitational potential: $\Phi(r)$ [J kg^{-1}]
Guiding center radius: R_g [AU]
GUT age: t_{GUT} [s]
GUT energy: E_{GUT} [TeV]
GUT temperature: T_{GUT} [K]
Gravitational constant: G [$\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$]
Growth factor: $D_+(t)$ [dimensionless]
Gunn-Peterson optical depth: τ_{GP} [dimensionless]
Gunn-Peterson oscillator strength: f_α [dimensionless]
Hamiltonian per unit mass: H [J kg^{-1}]
Harrison-Zeldovich power spectrum: $P(k)$ [μK^2]
Helium: He [element]
Helium mass fraction: Y [dimensionless]
Henry: H [unit]
Horizon angular size: θ_{hor} [rad]
Horizon angular size (at recombination): $\theta_{\text{hor,rec}}$ [rad]
Horizon distance: d_{hor} [Mpc]
Hubble constant: H_0 [$\text{km s}^{-1} \text{Mpc}$]
Hubble distance: d_H [Mpc]
Hubble time: t_H [Gyr]
Hydrogen (atomic): H [element]
Hydrogen (molecular): H_2 [element]
IMF: $\xi(m)$ [dimensionless]
IMF peak mass: M_{peak} [M_\odot]
Inflationary period: t_{inflate} [s]
Initial mass doubling time: (M_0/\dot{M}_0) [yr]
Isochrone potential: $\Phi(r)$ [J]
Jeans mass: M_J [M_\odot]
Jeans number: n_J [dimensionless]
Joule: J [unit]
Kinetic energy: E_{kin} [J]
Kinetic temperature: T_k [K]
Lagrangian per unit mass: \mathcal{L} [J]
Lagrangian per unit mass: \mathcal{L} [J kg^{-1}]
Line profile: $\phi(\nu)$ [???]
Lithium: Li [element]
Luminosity: L [erg s^{-1}]
Luminosity (Faber-Jackson): L_{FJ} [erg s^{-1}]
Luminosity (Tully-Fisher): L_{TF} [erg s^{-1}]
Luminosity distance: d_L [Mpc]
Luminosity of the Sun: L_\odot [W]
Luminosity of type Ia SN (at peak): L_{Ia} [L_\odot]
Luminosity distance: d_L [Mpc]
Lyman- α rest wavelength: λ_α [\AA]
Lyman- α temperature: T_α [K]
Magnetic field: \vec{B} [G]
Magnetic monopole density: n_M [m^{-3}]
Magnetic monopole mass: m_M [kg]
Magnetic permeability: μ [H m^{-1}]
Magnitude (absolute): M [mag]
Magnitude (apparent): m [mag]
Mass: m or M [kg]
Mass absorption coefficient: κ_ν [$\text{cm}^2 \text{g}^{-1}$]
Mass accretion rate index: η [dimensionless]
Mass of the stellar population: M_* [kg]
Mass of the Sun: M_\odot [kg]
Mass surface density: Σ [$\text{M}_\odot \text{pc}^{-2}$]
Mean free path: ℓ [m]
Mean molecular weight: μ [dimensionless]

Megaelectronvolt: MeV [unit]
Metallicity: Z [dimensionless]
Muller matrix: S_{ij} [μ dimensionless]
Multipole moment: C_ℓ [μK^2]
Neutral fraction of hydrogen: x_{HI} [dimensionless]
Neutron: n [particle]
Neutrino: ν [particle]
Neutrino temperature: T_ν [K]
Neutrino velocity: v_ν [km s^{-1}]
Newton: N [unit]
Number density: n [m^{-3}]
Number density of baryons: n_b [m^{-3}]
Number density of electrons: n_e [m^{-3}]
Number density of Lyman- α forest lines: $N_\alpha(z)$ [dimensionless]
Number density of neutrons: n_n [m^{-3}]
Number density of protons: n_p [m^{-3}]
Opacity: κ [$\text{cm}^2 \text{g}^{-1}$]
Opacity (dust): κ_d [$\text{cm}^2 \text{g}^{-1}$]
Optical depth: τ [dimensionless]
Parallax: p [rad or $^\circ$]
Parsec: pc [unit]
Peculiar velocity: v_{pec} [km s^{-1}]
Pericenter: r_1 [AU]
Period: P [yr]
Permittivity (vacuum): ϵ [F m^{-1}]
Photon: γ [particle]
Photon temperature: T_γ [K]
Photon scattering rate (ionized): Γ [s^{-1}]
Planck constant: h [$\text{m}^2 \text{kg s}^{-1}$]
Planck constant (reduced): \hbar [$\text{m}^2 \text{kg s}^{-1}$]
Planck energy: E_P [eV]
Planck function: $B_\nu(T)$ [$\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$]
Planck length: ℓ_P [m]
Planck mass: m_P [kg]
Planck time: t_P [s]
Polarization fraction: p [dimensionless]
Polarization fraction (max value): p_{max} [dimensionless]
Polarized angle: χ [rad]
Polarized intensity: P [Jy]
Positron: e^+ [particle]
Potential energy: E_{pot} [J]
Power spectrum: $P(k)$ [function]
Precession rate: Ω_p [rad yr^{-1}]
Proper distance: d_p [Mpc]
Proper motion: μ [$'' \text{year}^{-1}$]
Proton: p [particle]
R parameter: R_V [dimensionless]
Radial period: T_r [yr]
Radial unit vector: \hat{e}_r [dimensionless]
Radius (norm): r [pc]
Radius (vector): \vec{r} [pc]
Radius of curvature: R_0 [Mpc]
Radiative flux: F [W m^{-2}]
Rate of grain photoelectric heating: Γ_{PE} [erg s^{-1}]
Redshift: z [dimensionless]
Redshift (cosmological): z_{cos} [dimensionless]
Redshift of last scattering: z_{ls} [dimensionless]
Redshift of matter- Λ equality: $z_{m\Lambda}$ [dimensionless]
Redshift of radiation-matter equality: z_{rm} [dimensionless]
Redshift of thermal coupling: z_t [dimensionless]
Reduced Hubble constant: h_0 [$\text{km s}^{-1} \text{Mpc}$]

Reduced Planck constant: \hbar [$\text{m}^2 \text{kg s}^{-1}$]
Refractive index: $m(\omega)$ [dimensionless]
Relaxation time: t_{relax} [yr]
Rest mass of electron: m_e [kg]
Rest mass of neutron: m_n [kg]
Rest mass of proton: m_p [kg]
Rotational velocity (at Solar position): V_0 [km s^{-1}]
Scalar spectral index: n_s [dimensionless]
Scale factor: a [dimensionless]
Scale height: h_z [pc]
Scattering rate between hydrogen atoms: k_{1-0}^{HH} [s^{-1}]
Scattering rate between hydrogen atoms and electrons: k_{1-0}^{eH} [s^{-1}]
Scattering rate between hydrogen atoms and protons: k_{1-0}^{pH} [s^{-1}]
Schwarzschild radius: r_S [pc]
Semi-major axis: a [Mpc]
Siemen: S [unit]
Semi-minor axis: b [Mpc]
Sign of curvature: κ [dimensionless]
Silk mass: M_s [kg]
Size scale: ℓ [pc]
Solid angle: Ω [sr]
Sonic length: ℓ_s [pc]
Sonic mass: M_s [M_\odot]
Sound speed: v_s [m s^{-1}]
Spherical harmonics: $Y_{lm}(\theta, \phi)$ [dimensionless]
Spin temperature: T_s [K]
Specific intensity: I_ν [$\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$]
Speed of light: c [m s^{-1}]
Spin de-excitation rate via collisions for species i : k_{10}^i [$\text{cm}^3 \text{s}^{-1}$]
Spin temperature: T_s [K]
Star formation history: $\psi(z)$ [$M_\odot \text{year}^{-1} \text{Mpc}^{-3}$]
Star formation rate per unit area: Σ_{SFR} [$M_\odot \text{year}^{-1} \text{pc}^{-2}$]
Statistical weight: g [dimensionless]
Stefan-Boltzmann constant: σ [$\text{W m}^{-2} \text{K}^{-4}$]
Steradian: sr [unit]
Stokes I: Q [Jy]
Stokes Q: Q [Jy]
Stokes U: Q [Jy]
Stress energy tensor: $T_{\alpha\beta}$ [unit]
Sunyaev-Zeldovich temperature fluctuation: ΔT_{SZ} [K]
Sum of neutrino masses: Σm_ν [eV]
Surface brightness: μ [mag arcsec^{-2}]
Surface brightness (central): μ_0 [mag arcsec^{-2}]
Surface brightness at effective radius R_e : μ_e [mag arcsec^{-2}]
Temperature: T [K]
Temperature of the CMB: T_{CMB} [K]
Temperature of recombination: T_{rec} [K]
Temperature of the Sun: T_\odot [K]
Thermal energy: E_{th} [J]
Thomson cross section: σ_T [m^2]
Time: t [s or yr]
Time in units of the initial mass doubling time: τ [dimensionless]
Transfer function: $T(k)$ [???]
Tritium: T [element]
Two-point correlation function: $\xi(x)$ [dimensionless]
Velocity: v [m s^{-1}]
Velocity (circular): v_c [m s^{-1}]
Velocity (radial): v_r [m s^{-1}]
Velocity (rotational): v_{rot} [m s^{-1}]
Velocity (tangential): v_t [m s^{-1}]

Velocity dispersion: σ_v [m s^{-1}]
Velocity dispersion on size scale ℓ : $\sigma_v(\ell)$ [m s^{-1}]
Virial parameter: α_{vir} [dimensionless]
Virial temperature: T_{vir} [K]
Visual extinction: A_V [mag]
Volume: V [m^3]
Wavelength: λ [m]
Wavenumber (comoving): k [m^{-1}]

1.3 Useful Values

Age of the Earth: $t_{\oplus} = 4.5$ [Gyr]
Age of the Solar System: $t_{\text{SS}} = 4.6$ [Gyr]
Age of the Universe: $t_{\text{universe}} = 13.7$ [Gyr]
Angström: $\text{\AA} = 10^{-10}$ [m]
Astronomical Unit: $1 \text{ AU} = 1.5 \times 10^{11}$ [m]
Binding energy of deuterium: $E_{\text{D}} = 1.1$ [MeV]
Binding energy of helium: $E_{\text{He}} = 7$ [MeV]
Binding energy of hydrogen: $E_{\text{H}} = 13.7$ [MeV]
Chandrasekhar mass: $M_{\text{C}} = 1.4$ [M_{\odot}]
CMB peak photon wavelength: $\lambda_{\text{CMB}} = 2$ [mm]
CMB temperature: $T_{\text{CMB}} = 2.725$ [K]
CMB temperature fluctuations: $\Delta T/T \approx 10^{-5}$ [dimensionless]
CNB temperature: $T_{\text{CNB}} = 1.9$ [K]
Cosmological constant: $\Lambda = 1.11 \times 10^{-52}$ [m^{-2}]
Critical density (current): $\rho_{c,0} \approx 10^{-26}$ [kg m^{-3}]
Density of dark energy: $\rho_{\Lambda} = 10^{-27}$ [kg m^{-3}]
Density parameter of baryons: $\Omega_b \approx 0.044$ [dimensionless]
Density parameter of CMB: $\Omega_{\text{CMB}} \approx 5 \times 10^{-5}$ [dimensionless]
Density parameter of curvature: $\Omega_{\kappa} \approx 0.0$ [dimensionless]
Density parameter of cold dark matter: $\Omega_c \approx 0.23$ [dimensionless]
Density parameter of dark energy: $\Omega_{\Lambda} \approx 0.73$ [dimensionless]
Density parameter of matter: $\Omega_m \approx 0.27$ [dimensionless]
Density parameter of neutrinos: $\Omega_{\nu} < 0.12$ [dimensionless]
Density parameter of radiation: $\Omega_r \approx 5 \times 10^{-5}$ [dimensionless]
Dipole: $\ell = 1$ [dimensionless]
Electronvolt in Joules: $1 \text{ eV} = 1.6 \times 10^{-19}$ J
Electron radius (classical): $r_{e,0} = 2.82 \times 10^{-13}$ [cm]
Electroweak age: $t_{\text{ew}} \sim 10^{-12}$ [s]
Electroweak energy: $E_{\text{ew}} \sim 1$ [TeV]
Electroweak temperature: $T_{\text{ew}} \sim 10^{16}$ [K]
Energy of CMB photons: $E_{\gamma, \text{CMB}} \sim 6 \times 10^{-4}$ [eV]
Energy of nuclei fission: $E_{\text{fission}} \sim 1$ [MeV]
Energy of nuclei ionization: $E_{\text{ion}} \sim 10$ [eV]
GUT age: $t_{\text{GUT}} \sim 10^{-36}$ [s]
GUT energy: $E_{\text{GUT}} \sim 10^{12} - 10^{13}$ [TeV]
GUT temperature: $T_{\text{GUT}} \sim 10^{28}$ [K]
Helium mass fraction: $Y = 0.25$ [dimensionless]
Hubble constant: $H_0 = 70$ [$\text{km s}^{-1} \text{ Mpc}^{-1}$]
Hubble constant (original): $H_0 \approx 500$ [$\text{km s}^{-1} \text{ Mpc}^{-1}$]
Hubble distance: $d_H \sim 0.2$ [Mpc]
Hubble time: $t_H \sim 14$ [Gyr]
IMF normalization: $\int_{m_L}^{m_U} m \xi(m) dm = 1 M_{\odot}$
Inflationary period: $t_{\text{inflate}} = 10^{-35}$ [s]
Ionization energy of atomic hydrogen: $E_{\text{ion}}^{\text{H}} = 13.6$ [eV]
Ionization energy of atomic helium: $E_{\text{ion}}^{\text{He}} = 24.6$ [eV]
Ionization energy of molecular hydrogen: $E_{\text{ion}}^{\text{H}_2} = 11.26$ [eV]
Large cosmological scale: ~ 100 [Mpc]
Legendre Polynomials: P_l
Line profile normalization: $\int_0^{\infty} \phi(\nu) d\nu = 1$ [??]
Luminosity of the Sun: $L_{\odot} = 3.8 \times 10^6$ [W]
Luminosity of type Ia SN (at peak): $L_{\text{Ia}} = 4 \times 10^9$ [L_{\odot}]
Lyman-alpha rest wavelength: $\lambda_{\alpha} = 1216$ [\AA]
Magnitude (absolute) of the Sun: $M = 26.8$ [dimensionless]
Magnitude (apparent) of the Sun: $m = 4.74$ [dimensionless]
Mass of an electron: $m_e = 9.109 \times 10^{-31}$ [kg]
Mass of a neutron: $m_n = 1.67 \times 10^{-27}$ [kg]
Mass of a proton: $m_p = 1.67 \times 10^{-27}$ [kg]

Megaelectronvolt: $\text{MeV} = 10^{10.065} [\text{K}]$
Metallicity of the Sun: $Z \approx 0.02$ [dimensionless]
Milky Way luminosity: $L_{\text{MWG}} = 3.6 \times 10^{10} [L_{\odot}]$
Monopole: $\ell = 0$ [dimensionless]
Neutron half life: $t_n \sim 890 [\text{sec}]$ or $\sim 15 [\text{min}]$
Neutron-proton freezeout: $\frac{n_n}{n_p} \simeq \frac{1}{7}$ [dimensionless]
Neutron-proton rest mass-energy difference: $(m_n - m_p)c^2 = 1.3 [\text{MeV}]$
Number density of baryons: $n_{b,0} = 0.22 [\text{m}^{-3}]$
Number density of CMB photons: $n_{\gamma} = 4.11 \times 10^8 [\text{m}^{-3}]$
Number density ratio of baryons to CMB photons: $\eta \equiv \frac{n_{b,0}}{n_{\gamma}} = 5 \times 10^{-10}$ [dimensionless]
Parsec: $1 \text{ pc} = 206265 \text{ AU} = 3.1 \times 10^{16} \text{ m}$
Permittivity (vacuum): $\epsilon_0 = 8.85 \times 10^{-12} [\text{F m}^{-1}]$
Photoionization energy of hydrogen: $E_{\text{ion}}^{\text{H}} = 13.6 [\text{eV}]$
Planck energy: $E_P = 10^{16} [\text{TeV}]$
Planck length: $\ell_P = 1.6 \times 10^{-35} [\text{m}]$
Planck mass: $M_P = 2.2 \times 10^{-8} [\text{kg}]$
Planck temperature: $T_P = 1.4 \times 10^{32} [\text{K}]$
Planck time: $t_P = 5.4 \times 10^{-44} [\text{s}]$
Proper surface area: $A_p(t_0) [\text{Mpc}^2]$
Recombination age of Universe: $t_{\text{rec}} \sim 380,000 [\text{yr}]$
Recombination redshift: $z_{\text{rec}} \sim 1,100$ [dimensionless]
Reduced Hubble constant: $\frac{H_0}{100} = 0.70 [\text{km s}^{-1} \text{ Mpc}^{-1}]$
Redshift of radiation-matter equality: $z_{rm} \approx 5399$ [dimensionless]
Redshift of matter- Λ equality: $z_{m\Lambda} \approx 0.39$ [dimensionless]
Rest energy of an deuterium: $m_{\text{D}}c^2 = 2.225 [\text{MeV}]$
Rest energy of an electron: $m_e c^2 = 0.511 [\text{MeV}]$
Rest energy of a neutron: $m_n c^2 = 939.6 [\text{MeV}]$
Rest energy of a proton: $m_p c^2 = 938.3 [\text{MeV}]$
Rotational velocity (at Solar position): $V_0 = 220 [\text{km s}^{-1}]$
Scalar spectral index: $n_s \approx 1$ [dimensionless]
Scale factor (current): $a_0 = a(t_0) \equiv 1$ [dimensionless]
Scalefactor of radiation-matter equality: $a_{rm} \approx 2.8 \times 10^{-4}$ [dimensionless]
Scalefactor of matter- Λ equality: $a_{m\Lambda} \approx 0.75$ [dimensionless]
Seconds in a year: $1 \text{ yr} = 3.2 \times 10^7 [\text{s}]$
Seconds in a gigayear: $1 \text{ Gyr} = 3.2 \times 10^{16} [\text{s}]$
Sign of curvature (closed Universe): $\kappa > 0$ [dimensionless]
Sign of curvature (flat Universe): $\kappa = 0$ [dimensionless]
Sign of curvature (open Universe): $\kappa < 0$ [dimensionless]
Solar absolute magnitude: $M_{\odot} = 4.74 [\text{mag}]$
Solar apparent magnitude: $m_{\odot} = 26.8 [\text{mag}]$
Solar flux: $F_{\odot} = 1367 [\text{W m}^{-2}]$
Solar luminosity: $L_{\odot} = 3.8 \times 10^{26} [\text{W}]$
Solar mass: $M_{\odot} = 2.0 \times 10^{30} [\text{kg}]$
Solar mean photon energy: $\langle E_{\odot} \rangle = 1.3 [\text{eV}]$
Solar temperature: $T_{\odot} = 5800 [\text{K}]$
Speed of light: $c = 2.998 \times 10^8 [\text{m s}^{-1}]$
Stefan-Boltzmann constant: $\sigma = 5.67 \times 10^{-8} [\text{W m}^{-2} \text{ K}^{-4}]$
Supernova peak luminosity: $L_{\text{SN,max}} = 4 \times 10^9 L_{\odot} [\text{W}]$
Temperature at CMB decoupling: $k_B T_{\text{CMB,dec}} = 1/4 [\text{eV}]$
Thomson cross section: $\sigma_T = 0.665 \times 10^{-24} [\text{cm}^2]$
Time of radiation-matter equality: $t_{rm} \approx 4.7 \times 10^4 [\text{yr}]$
Time of matter- Λ equality: $t_{m\Lambda} \approx 9.8 [\text{Gyr}]$
Vacuum energy density: $\rho_{\text{vac}} = 10^{133} [\text{eV cm}^{-3}]$
21 cm energy: $E_{21 \text{ cm}} = 5.9 \times 10^{-6} [\text{eV}]$
21 cm rest frequency: $\nu_{21 \text{ cm}} = 1420 [\text{MHz}]$

1.4 Equations

Absolute magnitude:

$$M \equiv -2.5 \log \left(\frac{L}{L_0} \right) \text{ [mag]}$$

$$M \equiv -2.5 \log \left(\frac{L}{78.7 L_\odot} \right) \text{ [mag]}$$

Absorption coefficient: α_ν [cm^{-1}]

$$\alpha_\nu = n\sigma_\nu = \rho\kappa_\nu \text{ [cm}^{-1}\text{]}$$

Albedo:

$$\omega \equiv \frac{C_{\text{sca}}(\lambda)}{C_{\text{abs}}(\lambda) + C_{\text{sca}}(\lambda)} = \frac{C_{\text{sca}}(\lambda)}{C_{\text{ext}}(\lambda)} \text{ [dimensionless]}$$

Angular diameter distance:

$$D_A = D(1+z)^{-1} \text{ [pc]}$$

Angular momentum per unit mass:

$$\vec{L} \equiv \vec{r} \times \frac{d\vec{r}}{dt} \text{ [m}^2 \text{ s}^{-1} \text{ kg}^{-1}\text{]}$$

$$\vec{L} \equiv r^2 \dot{\phi} \text{ [m}^2 \text{ s}^{-1} \text{ kg}^{-1}\text{]}$$

Apocenter:

$$r_2 = a(1+e) \text{ [AU]}$$

Apparent magnitude:

$$m \equiv -2.5 \log \left(\frac{F}{F_0} \right) \text{ [mag]}$$

$$m \equiv -2.5 \log \left(\frac{F}{2.53 \times 10^{-8} \text{ W m}^{-2}} \right) \text{ [mag]}$$

Apparent-absolute magnitude relation:

$$M = m - 5 \log_{10} \left(\frac{d_L}{10 \text{ pc}} \right) \text{ [mag]}$$

$$= m - 5 \log_{10} \left(\frac{d_L}{1 \text{ Mpc}} \right) - 25 \text{ [mag]}$$

Azimuthal angle (change):

$$\Delta\psi = 2L \int_{r_1}^{r_2} \frac{dr}{r^2 \sqrt{2[E - \Phi(r)] - \frac{L^2}{r^2}}} \text{ [rad]}$$

Azimuthal period:

$$T_\psi = \frac{2\pi}{|\Delta\phi|} T_r \text{ [yr]}$$

Baryon fraction:

$$f_b \equiv \frac{\Omega_b}{\Omega_m} \text{ [dimensionless]}$$

Black hole mass-luminosity relation:

$$M_\bullet = 1.7 \times 10^9 \left(\frac{L_V}{10^{11} L_{V\odot}} \right)^{1.11} \text{ [M}_\odot\text{]}$$

Black hole mass-bulge relation:

$$M_\bullet = 2.9 \times 10^8 \left(\frac{M_{\text{bulge}}}{10^{11} \text{ M}_\odot} \right)^{1.05} \text{ [M}_\odot\text{]}$$

$$M_\bullet \approx 3 \times 10^{-3} M_{\text{bulge}}$$

Black hole mass-velocity dispersion relation:

$$M_\bullet = 2.1 \times 10^8 \left(\frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{5.64} \text{ [M}_\odot\text{]}$$

Black hole radius of influence:

$$r_{\text{BH}} = \frac{GM_\bullet}{\sigma_v^2} \sim 0.4 \left(\frac{M_\bullet}{10^6 \text{ M}_\odot} \right) \left(\frac{\sigma_v}{100 \text{ km s}^{-1}} \right)^{-2} \text{ [pc]}$$

Black hole radius of influence (angular):

$$\theta_{\text{BH}} = \frac{r_{\text{BH}}}{d} \sim 0.1 \left(\frac{M_{\bullet}}{10^6 M_{\odot}} \right) \left(\frac{\sigma_v}{100 \text{ km s}^{-1}} \right)^{-2} \left(\frac{d}{1 \text{ Mpc}} \right)^{-1} [\text{arcsec}]$$

Blackbody function:

$$B_{\nu}(T) = \frac{2h\nu^2}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1} [\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}]$$

Blackbody mean photon energy:

$$\langle E_{\text{bb}} \rangle = 2.7 k_B T [\text{eV}]$$

Blackbody peak photon energy:

$$E_{\text{bb,peak}} = 2.82 k_B T [\text{eV}]$$

Bohr magneton:

$$\mu_B \equiv \frac{e\hbar}{2m_e c} [\text{erg G}^{-1}]$$

Boltzmann factor:

$$\frac{n_i}{n_j} = e^{-\Delta mc^2/k_B T} [\text{dimensionless}]$$

CMB temperature fluctuations:

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi) [\text{dimensionless}]$$

Comoving sound horizon:

$$r_{\text{H,com}}(z) = \int_0^t \frac{cdt}{a(t)} = \int_0^{(1+z)^{-1}} \frac{cda}{a^2 H(a)} [\text{Mpc}]$$

Compton y-parameter:

$$y = \int \frac{k_B T}{m_e c^2} \sigma_T n_e dl [\text{dimensionless}]$$

Cosmological constant:

$$\Lambda = \frac{3H_0^2}{c^2} \Omega_{\Lambda} [\text{m}^{-2}]$$

Correlation function of CMB temperature anisotropies:

$$C(\theta) = \left\langle \frac{\delta T}{T}(\hat{n}) \frac{\delta T}{T}(\hat{n}') \right\rangle_{\hat{n} \cdot \hat{n}' = \cos \theta} [\text{dimensionless}]$$

$$C(\theta) = \frac{1}{4\pi} \sum_{\ell=0}^{\infty} (2\ell + 1) (C_{\ell}) P_{\ell}(\cos \theta) [\text{dimensionless}]$$

Collisional coupling coefficient:

$$\begin{aligned} x_c &= x_c^{\text{HH}} + x_c^{\text{eH}} + x_c^{\text{pH}} \\ &= \frac{T_*}{A_{10} T_{\gamma}} \left[k_{1-0}^{\text{HH}}(T_k) n_{\text{H}} + k_{1-0}^{\text{eH}}(T_k) n_e + k_{1-0}^{\text{pH}}(T_k) n_p \right] [\text{dimensionless}] \end{aligned}$$

Colour excess-HI column density relation:

$$E(B - V) = 1.7 \left(\frac{N_{\text{H}}}{10^{22} \text{ atoms cm}^{-2}} \right) [\text{mag}]$$

Coupling coefficient (total):

$$x_{\text{tot}} \equiv x_c + x_{\alpha} [\text{dimensionless}]$$

Critical density:

$$\rho_c \equiv \frac{3H_0^2}{8\pi G} [\text{g cm}^{-3}]$$

Critical density:

$$\rho_{\text{crit}} \sim \frac{c_s^2}{G \ell_s \ell} [\text{g cm}^{-3}]$$

Cross section (radiation pressure):

$$C_{\text{pr}}(\lambda) \equiv C_{\text{abs}}(\lambda) + (1 - \langle \cos \theta \rangle) C_{\text{sca}}(\lambda) [\text{cm}^2]$$

Crossing timescale:

$$t_{\text{cross}} = \frac{R}{v} \text{ [yr]}$$

Curvature term:

$$S_{\kappa}(r) = \begin{cases} R \sin(r/R), & (\kappa = +1) \\ r, & (\kappa = 0) \\ R \sinh(r/R), & (\kappa = -1) \end{cases}$$

Dark energy density:

$$\rho_{\Lambda} \equiv \frac{\Lambda}{8\pi G} \text{ [g cm}^{-3}\text{]}$$

Deceleration parameter:

$$q_0 = \Omega_{r,0} + \frac{1}{2}\Omega_{m,0} - \Omega_{\Lambda} \text{ [dimensionless]}$$

Density contrast:

$$\delta(\mathbf{x}, t) \equiv \frac{\rho(\mathbf{x}, t) - \langle \rho(t) \rangle}{\langle \rho(t) \rangle} \text{ [dimensionless]}$$

Density parameter:

$$\Omega_i \equiv \frac{\rho_i}{\rho_c} \text{ [dimensionless]}$$

Density parameter (total):

$$\Omega = \sum \Omega_i \equiv \sum \frac{\rho_i}{\rho_c} \text{ [dimensionless]}$$

Density parameter of curvature:

$$\Omega_{\kappa} = 1 - \Omega_0 \text{ [dimensionless]}$$

Density parameter of dark energy:

$$\begin{aligned} \Omega_{\Lambda} &\equiv \frac{\rho_{\Lambda}}{\rho_c} \\ &= \left(\frac{\Lambda}{8\pi G} \right) \left(\frac{8\pi G}{3H_0^2} \right) \\ &= \frac{\Lambda}{3H_0^2} \text{ [dimensionless]} \end{aligned}$$

Density parameter of matter:

$$\Omega_m(a) \equiv \frac{\rho_m}{\rho_c} a(t)^{-3} \text{ [dimensionless]}$$

Density parameter of radiation:

$$\Omega_r(a) \equiv \frac{\rho_r}{\rho_c} a(t)^{-4} \text{ [dimensionless]}$$

Density-redshift-scalefactor relation:

$$\bar{\rho}(z) = \bar{\rho}_0(1+z)^3 = \frac{\bar{\rho}_0}{a^3} \text{ [g cm}^{-3}\text{]}$$

Dipole moment:

$$\begin{aligned} \vec{\mu} &= q\vec{d} \text{ [C m]} \\ \vec{\mu} &= \alpha\vec{E} \text{ [C m]} \end{aligned}$$

Distance (moving cluster):

$$d = \frac{v_r \tan \theta}{\mu} \text{ [pc]}$$

Distance (parallax):

$$d = \left(\frac{p}{1''} \right)^{-1} \text{ [pc]}$$

Distance (photometric):

$$m - M = 5 \log \left(\frac{d}{1 \text{ pc}} \right) - 5 + A \text{ [mag]}$$

Distance (spectroscopic):

$$m_V - A_V - M_V = 5 \log \left(\frac{d}{1 \text{ pc}} \right) - 5 \text{ [mag]}$$

Distance modulus:

$$m - M \approx 43.17 - 5 \log_{10} \left(\frac{H_0}{70 \text{ km s}^{-1} \text{ Mpc}} \right) + 5 \log_{10} z + 1.086(1 - q_0)z \text{ [mag]}$$

Distance relation (low redshift):

$$d_p(t_0) \approx d_L \approx \frac{c}{H_0} z \text{ [Mpc]}$$

Distance-redshift relation (flat Universe):

$$d_L(\kappa = 0) = r(1 + z) = d_p(t_0)(1 + z) \text{ [Mpc]}$$

Doppler law:

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{obs}}} \text{ [dimensionless]}$$
$$\frac{v}{c} = \frac{-\Delta\nu}{\nu} = \frac{\nu_{\text{em}} - \nu_{\text{obs}}}{\nu_{\text{em}}} \text{ [dimensionless]}$$

Eccentricity:

$$e = \sqrt{1 - \frac{b^2}{a^2}} \text{ [dimensionless]}$$

Effective radius of dust grain:

$$a_{\text{eff}} \equiv \left(\frac{3V}{4\pi} \right)^{1/3} \text{ [\mu m]}$$

Einstein relations:

$$g_1 B_{12} = g_2 B_{21} \text{ [s}^{-1}\text{]}$$
$$A_{21} = \frac{2h\nu^3}{c^2} B_{21} \text{ [s}^{-1}\text{]}$$

Electric polarizability:

$$\alpha = \frac{\vec{\mu}}{\vec{E}} \text{ [C m}^2 \text{ V}^{-1}\text{]}$$

Electron radius (classical):

$$r_{e,0} = \frac{e^2}{m_e c^2} \text{ [cm]}$$

Elliptical $D_n - \sigma$ relation:

$$I_n \left(\frac{D_n}{2} \right)^2 \pi = 2\pi I_e R_e^2 \int_0^{D_n/(2R_e)} \text{ [erg s}^{-1} \text{ m}^{-2}\text{]}$$
$$D_n = 2.05 \times \left(\frac{\sigma_v}{100 \text{ km s}^{-1}} \right) \text{ [kpc]}$$

Efficiency factor (absorption):

$$Q_{\text{abs}} \equiv \frac{C_{\text{abs}}}{\pi a_{\text{eff}}^2} \text{ [cm}^{-2}\text{]}$$

Efficiency factor (extinction):

$$Q_{\text{ext}} \equiv Q_{\text{abs}} + Q_{\text{sca}} \text{ [cm}^{-2}\text{]}$$

Efficiency factor (scattering):

$$Q_{\text{sca}} \equiv \frac{C_{\text{sca}}}{\pi a_{\text{eff}}^2} \text{ [cm}^{-2}\text{]}$$

Energy density:

$$\Omega \equiv \frac{\rho}{\rho_c} = nE \text{ [dimensionless]}$$

Energy-redshift relation:

$$E = E_0(1 + z) \text{ [eV]}$$

Escape velocity:

$$v_{\text{esc}} = \sqrt{\frac{2GM}{r}} \text{ [km s}^{-1}\text{]}$$

Extinction:

$$\begin{aligned} A_\nu &\equiv m - m_0 \text{ [mag]} \\ &= -2.5 \log \left(\frac{I_{\nu,0}}{I_\nu} \right) \text{ [mag]} \\ &= -2.5 \log \left(\frac{F_{\nu,0}}{F_\nu} \right) \text{ [mag]} \\ &= 2.5 \log(e) \tau_\nu \text{ [mag]} \\ &= 1.086 \tau_\nu \text{ [mag]} \end{aligned}$$

Extinction coefficient for the MWG:

$$A_{V,\text{MWG}} = (3.1 \pm 0.1) E(B - V) \text{ [mag]}$$

Extinction coefficient in the Solar neighborhood:

$$A_V \approx \frac{d}{1 \text{ kpc}} \text{ [mag]}$$

Extinction cross section:

$$C_{\text{ext}}(\lambda) \equiv C_{\text{abs}}(\lambda) + C_{\text{sca}}(\lambda) \text{ [cm}^2\text{]}$$

Faber-Jackson relation:

$$L_{\text{FJ}} \propto \sigma_v^4 \text{ [erg s}^{-1}\text{]}$$

Farad:

$$1 \text{ F} \equiv \text{s}^4 \text{ A}^2 \text{ m}^{-2} \text{ kg}^{-1}$$

Flux:

$$F = \frac{L}{4\pi S_\kappa(r)^2} (1+z)^{-2} \text{ [erg s}^{-1} \text{ cm}^{-2}\text{]}$$

Flux (spectral):

$$F_\lambda(t) = \int_0^t \text{SFR}(t-t') S_{\lambda, Z(t-t')}(t') dt' \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}\text{]}$$

Friedmann equation:

$$\begin{aligned} \left(\frac{\dot{a}(t)}{a(t)} \right)^2 &= \left(\frac{H}{H_0} \right)^2 = \frac{8\pi G}{3} \rho - \frac{\kappa c^2}{R_0^2 a(t)^2} + \frac{\Lambda}{3} \\ \left(\frac{H}{H_0} \right)^2 &= \frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \Omega_{\Lambda,0} + \frac{1 - \Omega_0}{a^2} \end{aligned}$$

Gravitational acceleration:

$$g(r) = -\frac{d\Phi}{dr} \text{ [m s}^{-2}\text{]}$$

Gravitational potential energy:

$$E = -\frac{GMm}{R} \text{ [J]}$$

Growth factor:

$$D_+(t) \propto \frac{H(a)}{H_0} \int_0^a \frac{da'}{[\Omega_m/a' + \Omega_\Lambda a'^2 - (\Omega_m + \Omega_\Lambda - 1)]^{3/2}} \text{ [dimensionless]}$$

Gunn-Peterson optical depth:

$$\begin{aligned} \tau_{\text{GP}} &= \frac{\pi e^2}{m_e c^2} f_\alpha \lambda_\alpha H^{-1}(z) n_{\text{HI}} \text{ [dimensionless]} \\ \tau_{\text{GP}}(z) &= 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13} \right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02} \right) \left(\frac{1+z}{7} \right)^{3/2} \left(\frac{n_{\text{HI}}}{n_{\text{H}}} \right) \text{ [dimensionless]} \end{aligned}$$

Hamilton's equations:

$$\dot{q}_i \equiv \frac{\partial H}{\partial p_i}; \quad \dot{p} \equiv -\frac{\partial H}{\partial q_i}$$

Harrison-Zeldovich power spectrum:

$$P(k) \propto k^{n_s-1} \text{ [}\mu\text{K}^2\text{]}$$

Helium mass fraction:

$$Y = \frac{4 \times n_n/2}{n_n + n_p} = \frac{2}{1 + n_n/n_p} \text{ [dimensionless]}$$

Henry (unit):

$$1 \text{ H} \equiv 1 \text{ kg m}^2 \text{ s}^{-2} \text{ A}^{-2}$$

Horizon angular size at recombination:

$$\theta_{H,\text{rec}} \approx \sqrt{\frac{\Omega_m}{z_{\text{rec}}}} \sim \frac{\sqrt{\Omega_m}}{30} \sim \sqrt{\Omega_m} 2 \text{ [}^\circ\text{]}$$

Hubble constant:

$$H_0(t) \equiv \frac{\dot{a}_0(t)}{a_0(t)} = \dot{a}_0(t) \text{ [km s}^{-1} \text{ Mpc]}$$

Hubble distance:

$$d_H \equiv \frac{c}{H(t)} \text{ [Mpc]}$$

Hubble time:

$$t_H \equiv ct_H = \frac{1}{H_0(t)} \text{ [Gyr]}$$

Hubble's law:

$$v = H_0 d \text{ [km s}^{-1}\text{]}$$

IMF peak mass:

$$M_{\text{peak}} \propto \frac{c_s^3}{\sqrt{G^3 \rho}} \text{ [M}_\odot\text{]}$$
$$M_{\text{peak}} \propto \frac{c_s^2 \ell_s}{G} \text{ [M}_\odot\text{]}$$

IMF (Salpeter):

$$\xi(m) \propto m^{-2.35} \text{ [dimensionless]}$$

Isochrone potential:

$$\Phi(r) = -\frac{GM}{b + \sqrt{b^2 + r^2}} \text{ [J]}$$

Jeans mass:

$$M_J \equiv \frac{\pi^{5/2}}{6} \left(\frac{c_s^2}{G} \right)^{3/2} \frac{1}{\sqrt{\rho}} \text{ [M}_\odot\text{]}$$

Kepler's third law:

$$P = \sqrt{\frac{4\pi^2}{G(m_1 + m_2)}} a^3 \text{ [yr]}$$

Legendre Polynomials:

$$P_0(x) = 1 \text{ [dimensionless]}$$
$$P_1(x) = x \text{ [dimensionless]}$$
$$P_2(x) = \frac{1}{2}(3x^2 - 1) \text{ [dimensionless]}$$

Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \text{ [N]}$$

Luminosity:

$$L = 4\pi R^2 \sigma T^4 \text{ [erg s}^{-1}\text{]}$$

Luminosity (Faber-Jackson):

$$L_{\text{FJ}} \propto \sigma_v^\alpha \text{ [erg s}^{-1}\text{]}$$

Luminosity (Tully-Fisher):

$$L_{\text{TF}} \propto v_{\text{max}}^\alpha \text{ [erg s}^{-1}\text{]}$$
$$= \left(\frac{M}{L} \right)^{-2} \left(\frac{1}{G^2 \langle I \rangle} \right) v_{\text{max}}^4 \text{ [erg s}^{-1}\text{]}$$

Luminosity distance:

$$d_L \equiv \sqrt{\frac{L}{4\pi F}} \text{ [Mpc]}$$
$$d_L(z \ll 1) \approx \frac{c}{H_0} z \left(1 + \frac{q_0}{2} z\right) \text{ [Mpc]}$$
$$d_L(\kappa = 0) \approx \frac{c}{H_0} z \left(1 + \frac{1 - q_0}{2} z\right) \text{ [Mpc]}$$

Luminosity distance-redshift relation:

$$d_L = d(1 + z) \text{ [Mpc]}$$

Magnetic field:

$$\vec{B} = \mu \vec{H} \text{ [G]}$$

Magnetic monopole density:

$$n_M(t_{\text{GUT}}) \sim \frac{1}{(2ct_{\text{GUT}})^3} \sim 10^{82} \text{ [m}^{-3}\text{]}$$

Magnitude (absolute):

$$M \equiv -2.5 \log_{10} \left(\frac{L}{L_0} \right) \text{ [mag]}$$

Magnitude (apparent):

$$m \equiv -2.5 \log_{10} \left(\frac{F}{F_0} \right) \text{ [mag]}$$

Matter density-scale factor relation:

$$\rho_m = \rho_{m,0} a^{-3} \text{ [g cm}^{-3}\text{]}$$

Maxwell-Boltzmann equation:

$$n = g \left(\frac{mk_B T}{2\pi \hbar^2} \right)^{3/2} \exp \left(-\frac{E}{k_B T} \right) \text{ [m}^{-3}\text{]}$$
$$= g \left(\frac{mk_B T}{2\pi \hbar^2} \right)^{3/2} \exp \left(-\frac{h\nu}{k_B T} \right) \text{ [m}^{-3}\text{]}$$

Mean free path:

$$\ell_{\text{mfp}} = \frac{1}{n\sigma} \text{ [pc]}$$

Mean molecular weight:

$$\mu \equiv \frac{\rho}{nm} \text{ [dimensionless]}$$

Metallicity index:

$$[\text{X}/\text{H}] \equiv \log \left(\frac{n(\text{X})}{n(\text{H})} \right)_* - \log \left(\frac{n(\text{X})}{n(\text{H})} \right)_\odot \text{ [dimensionless]}$$

Neutrino velocity:

$$v_\nu \sim 150(1 + z) \left(\frac{m_\nu}{1 \text{ eV}} \right)^{-1} \text{ [km s}^{-1}\text{]}$$

Newton:

$$1 \text{ N} \equiv \frac{1 \text{ J}}{\text{m}}$$

Number density:

$$n = \frac{\rho}{\mu m_H} \text{ [cm}^{-3}\text{]}$$

Number density of Lyman- α forest lines:

$$N_\alpha(z) \propto (1 + z)$$

Optical depth:

$$\tau = \int_0^s \alpha_\nu ds \text{ [dimensionless]}$$

Peculiar velocity:

$$v_{\text{pec}} = c \left(\frac{z - z_{\text{cos}}}{1 + z} \right) \text{ [km s}^{-1}\text{]}$$

Pericenter:

$$r_1 = a(1 - e) \text{ [AU]}$$

Photon energy:

$$E_\gamma = h\nu \text{ [eV]}$$

Photon scattering rate (ionized):

$$\Gamma = \frac{c}{\ell_{\text{mfp}}} = n_e \sigma_e c = n_b \sigma_e c = \left(\frac{n_{b,0}}{a^3} \right) \sigma_e c = \frac{4.4 \times 10^{-21} a^3}{\text{[s}^{-1}\text{]}}$$

Planck function:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\text{]}$$

Polarization fraction:

$$p(\lambda^2) = \frac{P}{I} \text{ [dimensionless]}$$

Polarization fraction (max value):

$$0 < p_{\text{max}} \leq 0.09 \left[\frac{E(B - V)}{\text{mag}} \right] \approx 0.03 \left[\frac{A_V}{\text{mag}} \right] \text{ [dimensionless]}$$
$$0 < p_V \lesssim 0.03 \tau_V \text{ [dimensionless]}$$

Polarized angle:

$$\chi = \frac{1}{2} \arctan \left(\frac{U}{Q} \right) \text{ [rad]}$$

Polarized intensity:

$$P = \sqrt{Q^2 + U^2} = pI \text{ [Jy]}$$

Power spectrum:

$$P(k) = 2\pi \int_0^\infty x^2 \frac{\sin(kx)}{kx} \xi(x) dx \text{ [dimensionless]}$$

Precession rate:

$$\Omega_p = \frac{\psi_p}{T_r} = \frac{\Delta\psi - 2\pi}{T_r} \text{ [rad yr}^{-1}\text{]}$$

Proper distance:

$$d_p(t_0) = c \int_t^{t_0} \frac{dt}{a(t)} \text{ [Mpc]}$$
$$d_p(t_0, z \ll 1) \approx \frac{c}{H_0} z \left(1 - \frac{1 + q_0}{2} z \right) \text{ [Mpc]}$$

Proper motion:

$$\mu = \frac{v_t}{d} \text{ [arcsec yr]}$$

Proper surface area:

$$A_p(t_0) = 4\pi S_\kappa(r)^2 \text{ [Mpc}^2\text{]}$$

R parameter:

$$R_V \equiv \frac{A_V}{A_B - A_V} \equiv \frac{A_V}{E(B - V)} \text{ [dimensionless]}$$

Radial period:

$$T_r = 2 \int_{r_1}^{r_2} \frac{dr}{\sqrt{2[E - \Phi(r)] - \frac{L^2}{r^2}}} \text{ [yr]}$$
$$= T_\psi = \frac{a^2}{L} \sqrt{1 - e^2} = 2\pi \sqrt{\frac{a^3}{GM}} \text{ [yr]}$$

Radiation density-scale factor relation:

$$\rho_r = \rho_{r,0} a^{-4} \text{ [g cm}^{-3}\text{]}$$

Radiative transfer equation:

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1} \text{ pc}^{-1}\text{]}$$

Random walk:

$$d = \sqrt{N} \ell \text{ [m]}$$

Rate of grain photoelectric heating:

$$\Gamma_{\text{PE}} \approx 4.0 \times 10^{-26} \chi_{\text{FUV}} Z'_d e^{-\tau_d} \text{ [erg s}^{-1}\text{]}$$

Rayleigh-Jeans limit:

$$I_\nu = \frac{2k_B T \nu^2}{c^2} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\text{]}$$

Redshift of thermal coupling:

$$z_t \approx 140 \left(\frac{\Omega_b h^2}{0.022} \right)^{2/5} \text{ [dimensionless]}$$

Redshift-wavelength-scalefactor relation:

$$\frac{1}{1+z} = \frac{\lambda}{\lambda_0} = a \text{ [dimensionless]}$$

Refractive index:

$$m = \sqrt{\sigma} \text{ [dimensionless]}$$

Relaxation time:

$$t_{\text{relax}} \approx \frac{R}{6v} \frac{N}{\ln(N/2)} \text{ [yr]}$$
$$t_{\text{relax}} = \frac{t_{\text{cross}}}{6} \frac{N}{\ln(N/2)} \text{ [yr]}$$

Robertson-Walker metric:

$$ds^2 = c dt^2 - a(t)^2 \left(\frac{dx^2}{1 - \kappa x^2 / R^2} + x^2 \Omega^2 \right)$$

Rotational velocity (at Solar position):

$$V_0 = \sqrt{\frac{GM(< R)}{R_0}} \text{ [m s}^{-1}\text{]}$$

Saha equation:

$$\frac{n_{i+1}}{n_i} = T^{3/2} e^{(-1/T)} \text{ [dimensionless]}$$

Scale factor evolution (radiation-dominated):

$$a_m(t) \propto t^{1/2} \text{ [dimensionless]}$$

Scale factor evolution (matter-dominated):

$$a_m(t) \propto t^{2/3} \text{ [dimensionless]}$$

Scale factor evolution (Λ -dominated):

$$a_\Lambda(t) \propto e^{Ht} \text{ [dimensionless]}$$

Scale factor-redshift relation:

$$a = \frac{1}{1+z} \text{ [dimensionless]}$$

Schmidt-Kennicutt law:

$$\frac{\Sigma_{\text{SFR}}}{\text{M}_\odot \text{ year}^{-1} \text{ kpc}^{-2}} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\text{gas}}}{\text{M}_\odot \text{ pc}^{-2}} \right)^{1.4 \pm 0.15}$$

Schwarzschild radius:

$$r_S \equiv \frac{2GM}{c^2} = 2.95 \left(\frac{M}{\text{M}_\odot} \right) \text{ [km]}$$

Serkowski Law:

$$p(\lambda) \approx p_{\text{max}} \exp \left[-K \ln^2 \left(\frac{\lambda}{\lambda_{\text{max}}} \right) \right] \text{ [dimensionless]}$$

Siemen:

$$1 \text{ S} \equiv \text{kg}^{-1} \text{ m}^{-2} \text{ s}^3 \text{ A}^2$$

Solid angle:

$$\Omega = \frac{A}{r^2} \text{ [sr]}$$

Sonic mass:

$$M_s \approx \frac{c_s^2 \ell_s}{G} \text{ [M}_\odot\text{]}$$

Sound speed:

$$c_s = \sqrt{\frac{\partial P}{\partial \rho}} \text{ [m s}^{-1}\text{]}$$
$$c_s \sim \sqrt{\frac{k_B T}{\mu m}} \text{ [m s}^{-1}\text{]}$$

Spin temperature:

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c} \text{ [K}^{-1}\text{]}$$

Spin temperature of 21 cm:

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} \exp\left(-\frac{0.068 \text{ K}}{T_s}\right) \text{ [dimensionless]},$$

Star formation history:

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [1+z/2.9]^{5.6}} \text{ [M}_\odot \text{ year}^{-1} \text{ Mpc}^{-3}\text{]}.$$

Star formation rate:

$$\text{SFR} = -\frac{dM_{\text{gas}}}{dt} \text{ [M}_\odot \text{ yr}^{-1}\text{]}$$

Star formation rate per unit area:

$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4} \text{ [M}_\odot \text{ year}^{-1} \text{ pc}^{-2}\text{]}$$

Stefan-Boltzmann constant:

$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} \text{ [W m}^{-2} \text{ K}^{-4}\text{]}$$

Stefan-Boltzmann Law:

$$F = \sigma T^4 \text{ [W m}^{-2}\text{]}$$

Sunyaev-Zeldovich temperature fluctuation:

$$\frac{\Delta T_{\text{SZE}}}{T_{\text{CMB}}} = f(x)y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T dl \text{ [dimensionless]}$$
$$\frac{\Delta T_{\text{SZ}}}{T_{\text{CMB}}} = -\tau_e \left(\frac{v_{\text{pec}}}{c}\right) \text{ [dimensionless]}$$

Surface brightness (bulge):

$$\mu_{\text{bulge}} = \mu_e + 8.3268 \left[\left(\frac{R}{R_e} \right)^{1/4} - 1 \right] \text{ [mag arcsec}^{-2}\text{]}$$

Surface brightness (disk):

$$\mu_{\text{disk}} = \mu_0 + 1.09 \left(\frac{R}{h_R} \right) \text{ [mag arcsec}^{-2}\text{]}$$

Temperature-redshift-scalefactor relation:

$$T = (1+z)T_0 = \frac{T_0}{a} \text{ [K]}$$

Thomson cross section:

$$\sigma_T = \frac{8\pi}{3} r_{e,0}^2 \text{ [m}^2\text{]}$$

Time in units of the initial mass doubling time:

$$\tau = \frac{t}{(M_0/\dot{M}_0)} \text{ [dimensionless]}$$

Tired Light Hypothesis energy scaling:

$$E = E_0 e^{(-r/R_0)} \text{ [eV]}$$

Tully-Fisher relation:

$$L_{\text{TF}} \propto v_{\text{max}}^4 \text{ [erg s}^{-1}\text{]}$$

Two-point correlation function:

$$\xi(r) = \left(\frac{r}{r_0} \right)^{-1.7} \text{ [dimensionless]}$$

Uncertainty Principle:

$$\sigma_x \sigma_p \geq \frac{\hbar}{2} \text{ [J s]}$$
$$\Delta E \Delta t \geq \frac{\hbar}{2} \text{ [J s]}$$

Velocity (circular):

$$v_c = \sqrt{\frac{GM}{r}} \text{ [m s}^{-1}\text{]}$$

Velocity (radial):

$$v_r = \left(\frac{\Delta \lambda}{\lambda_0} \right) c \text{ [m s}^{-1}\text{]}$$

Velocity (tangential):

$$v_t = d\mu = 4.74 \left(\frac{d}{1 \text{ pc}} \right) \left(\frac{\mu}{1'' \text{ year}^{-1}} \right) \text{ [m s}^{-1}\text{]}$$

Virial parameter:

$$\alpha_{\text{vir}} \sim \frac{\sigma_v R}{GM} \text{ [dimensionless]}$$

Virial theorem:

$$E_{\text{pot}} = -2E_{\text{kin}} \text{ [J]}$$
$$E_{\text{tot}} = \frac{1}{2}E_{\text{pot}} \text{ [J]}$$

Wavelength-redshift relation:

$$\lambda_0 = \frac{1}{a(t)} \lambda = (1+z) \lambda \text{ [m]}$$

Wien's Law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\text{]}$$
$$B_\nu(T) \approx \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T)} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\text{]}$$
$$B_\nu(T) \approx \frac{2h\nu^3}{c^2} \exp\left(\frac{-h\nu}{k_B T}\right) \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\text{]}$$

1.5 General Notes

- $k_B(300\text{ K}) \sim \frac{1}{40}\text{ eV}$
- $k_B(11,000\text{ K}) \sim 1\text{ eV}$
- $k_B(10^7\text{ K}) \sim 1\text{ keV}$
- Systems in thermal equilibrium satisfy normal populations of $(n_1/g_1) > (n_2/g_2)$; inverted populations satisfy $(n_1/g_1) < (n_2/g_2)$ (e.g., masers).
- If a particle scatters with a rate greater than the expansion rate of the Universe, that particle remains in equilibrium.
- Ordinary (i.e., baryonic) matter contributes at most 5% of the Universe's critical density.
- Multipole moment $\ell = 1$ and $\ell = 2$ are the dipole and quadrupole moment, respectively.
- The greatest baryon contribution to the density comes not from stars in galaxies, but rather from gas in groups of galaxies; in these groups, $\Omega \sim 0.02$.
- The ratio of the neutrino temperature T_ν to the CMB temperature T_{CMB} is $\frac{T_\nu}{T_{\text{CMB}}} = \left(\frac{4}{11}\right)^{1/3}$.
- We expect photons to decouple from matter when the Universe is already well into the matter-dominated era (i.e., not in the radiation-dominated era).
- When the Universe was only one second old, the mean-free-path of a photon was about the size of an atom.
- Nuclear binding energies are typically in the MeV range, which explains why Big Bang nucleosynthesis occurs at temperatures a bit less than 1 MeV even though nuclear masses are in the GeV range.
- The electron-positron energy threshold is $\sim 10^{10}\text{ K}$, above which there exist thermal populations of both electrons and neutrinos to make the reaction $p + e^- \leftrightarrow n + \nu$ go equally well in either direction.
- Thermodynamically, nucleons with greater binding energies are more energetically favourable.
- Simplest way to form helium is via deuterium fusion rather than the improbable coincidence of 2 protons and 2 neutrons all arriving at the same place simultaneously to make ${}^4\text{He}$ in one go.
- Nucleosynthesis starts at about 10^{10} K when the Universe was about 1 s old, and effectively ends when it has cooled by a factor of 10, and is about 100 times older.
- Primordial elemental abundances: 75% H, 25% He, trace Li.
- A normal population of states in LTE satisfies $(n_1/g_1)/(n_2/g_2) > 1$ via the Maxwell-Boltzmann equation; inverted populations such as masers satisfy $(n_1/g_1)/(n_2/g_2) < 1$.
- The solid angle subtended by a complete sphere is $4\pi\text{ sr}$.
- Just as the period of a Cepheid tells you its luminosity, the rise and fall time of a type Ia SN tells you its peak luminosity.
- The average Type Ia has a peak luminosity of $L = 4 \times 10^9 L_\odot$ which is 100,000 times brighter than even the brightest Cepheid variable.
- The Hubble distance d_H is the distance between the Earth and any astrophysical object receding away from us at the speed of light.
- At $z = 10^9$, the Jeans mass is $M_J \sim M_\odot$; at $z = 10^6$, the Jeans mass is $M_J \sim M_{\text{gal}}$.
- Apparent magnitudes $0 < m < 6$ are typically visible to the naked eye.
- The absolute magnitude of a light source M is defined as the apparent magnitude m that it would have if it were at a luminosity distance of $d_L = 10\text{ pc}$.
- The apparent magnitude is really nothing more than a logarithmic measure of the flux, and the absolute magnitude is a logarithmic measure of the luminosity.

- When space is positively curved, the proper surface area is $A_p(t_0) < 4\pi r^2$, and the photons from distance r are spread over a smaller area than they would be in flat space. When space is negatively curved, $A_p(t_0) > 4\pi r^2$, and photons are spread over a larger area than they would be in flat space.
- The Benchmark Model has a deceleration parameter of $q_0 \approx 0.55$.
- The angular distribution of the CMB temperature reflects the matter inhomogeneities at the redshift of decoupling of radiation and matter.
- The CMB is linearly polarized at the 10% level.
- CMB polarization probes the epoch of last scattering directly as opposed to the temperature fluctuations which may evolve between last scattering and the present. Moreover, different sources of temperature anisotropies (scalar, vector, and tensor) give different patterns in the polarization: both in its intrinsic structure and in its correlation with the temperature fluctuations themselves.
- The sound speed in the photon-dominated fluid of the early Universe is given by $c_s \approx c/\sqrt{3}$. Thus, the sound horizon is about a factor of $\sqrt{3}$ smaller than the event horizon at this time.
- At recombination, the free electrons recombined with the hydrogen and helium nuclei, after which there are essentially no more free electrons which couple to the photon field. Hence, after recombination the baryon fluid lacks the pressure support of the photons, and the sound speed drops to zero – the sound waves do no longer propagate, but get frozen in.
- In a universe which is dominated by dark matter the expected CMB fluctuations on small angular scales are considerably smaller than in a purely baryonic universe.
- The number density of each of the three flavors of neutrinos (ν_e , ν_μ , and ν_τ) has been calculated to be 3/11 times the number density of CMB photons. This means that at any moment, about twenty million cosmic neutrinos are zipping through your body.
- Due to the steep slope of the IMF, most of the stellar mass is contained in low-mass stars; however, since the luminosity of main-sequence stars depends strongly on mass, approximately as $L \propto M^3$, most of the luminosity comes from high-mass stars.
- Cooling by the primordial gas is efficient only above $T \gtrsim 2 \times 10^4$ K since metal lines cannot contribute to the cooling.
- Whereas in enriched gas molecular hydrogen is formed on dust particles, the primordial gas had no dust so H_2 must form in the gas phase itself, rendering its abundance very small.
- Even a tiny neutral fraction, $X_{HI} \sim 10^{-4}$, gives rise to complete GP absorption due to the large absorption cross section of $Ly\alpha$.
- The key to the detectability of the 21 cm signal hinges on the spin temperature T_s . Only if this temperature deviates from the background temperature, will a signal be observable.
- The spin temperature becomes strongly coupled to the gas temperature when $x_{tot} \equiv x_c + x_\alpha \gtrsim 1$ and relaxes to T_γ when $x_{tot} \ll 1$.
- The ratio of black hole mass and bulge mass is approximately 1/300. In other words, 0.3% of the baryon mass that was used to make the stellar population in the bulge of these galaxies was transformed into a central black hole.
- It is not hard to show that L is actually the length of the vector $\vec{r} \times \dot{\vec{r}}$, and hence that $r^2 \dot{\phi} \equiv L$ is just a restatement of the conservation of angular momentum. Geometrically, L is equal to twice the rate at which the radius vector sweeps out area.
- The density at which grains and gas become well-coupled is around $10^4 - 10^5 \text{ cm}^{-3}$, which is higher than the typical density in a GMC.
- The energy associated with the 21 cm transition is $\ll 1$ K, so even in cold regions atomic hydrogen can be excited.
- Since cosmic rays are relativistic particles, they have much lower interaction cross sections, and thus are able to penetrate into regions where light cannot.

- Sightlines through diffuse gas in the MW have extinction parameters of $R_V \approx 3.1$ as an average value.
- At submillimeter frequencies and above, real materials have only a negligible response to an applied magnetic field – this is because the magnetization of materials is the result of aligned electron spins and electron orbital currents, and an electron spin (or orbit) can change direction only on time scales longer than the period for the electron spin (or orbit) to precess in the local (microscopic) magnetic fields within atoms and solids. These fields are at most $B_i \lesssim 10$ kG, and the precession frequencies are $\omega_p \approx \mu_B B_i / \hbar \lesssim 10^{10} \text{ s}^{-1}$.
- Ray-tracing arguments would lead us to expect the extinction cross section to be equal to the geometric cross section, but diffraction around the target leads to additional small-angle scattering, with the total extinction cross section equal to twice the geometric cross section.