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Appendix A

Glossary

The aim here is to provide a convenient list of definitions, covering units, constants, acronyms, and terms used in this book and/or in cited literature that might not be familiar to the reader. Units and constants listed in Section A.1 should be regarded as supplementary to standard Système Internationale (SI) units and the common physical constants. Completeness is not guaranteed!

A.1 Units and Constants

Astronomical Unit (AU): Mean Sun–Earth distance; $1\ \mathrm{AU} = 1.496 \times 10^{11}\ \mathrm{m}$.

Dex: Quasi-unit of logarithm to base 10, sometimes used to express abundance ratios: $\log 10 = 1$ dex, $\log 100 = 2$ dex, etc.

Jansky (Jy): Unit of luminous flux density: $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$. Similarly, $1\ \mathrm{mJy} = 10^{-3}$ Jy.

Magnetic flux density: $1\ \mu\mathrm{G} = 10^{-10}$ T (preferred unit for interstellar values).

Magnitude (mag): Dimensionless logarithmic measure of brightness in stellar astronomy, also used for interstellar quantities such as extinction and reddening deduced from stellar data. See also Section A.3.

Parsec (pc): Unit of distance based on stellar annual parallax; $1\ \mathrm{pc} = 3.086 \times 10^{16}\ \mathrm{m}$. Similarly, kiloparsec ($1\ \mathrm{kpc} = 10^3$ pc), megaparsec ($1\ \mathrm{Mpc} = 10^6$ pc).

Parts per million (ppm): Measure of abundance ratio by number, usually relative to hydrogen; e.g., an estimate of the solar O to H abundance ratio is $4.9 \times 10^{-4} = 490$ ppm.

Solar luminosity: $1\ \mathrm{L_\odot} = 3.826 \times 10^{26}$ W.

Solar mass: $1\ \mathrm{M_\odot} = 1.989 \times 10^{30}$ kg.

Solar radius: $1\ \mathrm{R_\odot} = 6.960 \times 10^{8}$ m.

Units of time: 1 Myr $= 10^6$ years; 1 Gyr $= 10^9$ years.

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A.2 Common Acronyms

AGB: Asymptotic giant branch.

ALMA: Atacama Large Millimeter–submillimeter Array (telescope).

AME: Anomalous microwave emission.

CDE: Continuous distribution of ellipsoids.

CS: Circumstellar.

DDA: Discrete dipole approximation.

DG: Davis–Greenstein (grain alignment mechanism).

DGL: Diffuse galactic light.

DIBs: Diffuse interstellar bands.

EMT: Effective medium theory.

ERE: Extended red emission.

EUV: Extreme ultraviolet.

FIR: Far infrared.

FM: Fitzpatrick and Massa (empirical extinction formula).

FUV: Far ultraviolet.

FWHM: Full-width at half-maximum (intensity), e.g., of a spectral feature.

GC: Galactic center (of the Milky Way).

GEMS: Glass with embedded metal and sulfides.

HAC: Hydrogenated amorphous carbon.

HD: Henry Draper (star catalog).

HR: Hertzsprung–Russell (diagram).

HVC: High-velocity cloud.

IDP: Interplanetary dust particle.

IMF: Initial (stellar) mass function.

IRAS: Infrared Astronomical Satellite.

IRC: Infrared catalog (of stars).

IRS: Infrared source.

ISM: Interstellar medium.

ISO: Infrared Space Observatory.

ISRF: Interstellar radiation field.

IUE: International Ultraviolet Explorer (satellite).

JWST: James Webb Space Telescope.

LMC: Large Magellanic Cloud.

MIR: Mid-infrared.

MRN: Mathis, Rumpl and Nordsieck (grain size distribution function).

NGC: New General Catalog (of star clusters, nebulae and galaxies).

NIR: Near infrared.

ORM: Organic refractory matter.

PAH: Polycyclic aromatic hydrocarbon.

PMS: Pre-main-sequence (star).

PN: Planetary nebula (plural PNe).

ppm: Parts per million (abundance ratio).

RATs: Radiative alignment torques.

RCB: R Coronae Borealis (star).

SED: Spectral energy distribution.

SMC: Small Magellanic Cloud.

SN: Supernova (plural SNe).

SNR: Supernova remnant.

SPM: Superparamagnetic.

UV: Ultraviolet.

VBS: Very broadband structure.

VSG: Very small grain.

WR: Wolf-Rayet (star).

YSO: Young stellar object.

A.3 Physical, Chemical and Astrophysical Terms

Accretion: Growth of solids by physical attachment of colliding particles. The term may be used in the context of grain–grain coagulation or attachment of gaseous particles to a grain to form a surface layer. Accretion in a protoplanetary disk is considered to be the initial phase of planet formation.

Adsorption: Adhesion to a solid surface, a term commonly used to describe the sticking of gaseous atoms or molecules to interstellar dust grains. Adsorption may be physical (physisorption, arising from van der Waals forces), or the result of a chemical bond between surface atoms and the attached species (chemisorption).

Aliphatic hydrocarbons: Organic molecules composed of carbon chains with attached H atoms. Single-bonded chains (alkanes) have the generic formula

CH_3–$(CH_2)_n$–CH_3 where $n \geqslant 0$ is an integer. Chains that contain one or more C=C bonds are referred to as olefinic.

Asymptotic giant branch (AGB): A region of the Hertzsprung–Russell diagram occupied by stars of intermediate mass (0.8–8 $M_\odot$) in their late phases of red-giant evolution. An AGB star typically has a core composed mostly of carbon and oxygen, surrounded by helium and hydrogen-burning shells. Deep convection currents and pulsational instabilities may lead to the atmosphere becoming enriched in carbon. After periods of increasingly rapid mass loss, an AGB star sheds its outer layers to form a planetary nebula and its core becomes a white dwarf. A star undergoing the brief transition from AGB to PN (a post-AGB star) is sometimes described by the potentially misleading term "protoplanetary nebula."

Carbon star: A red giant that has a carbon-enriched atmosphere (C/O $\gtrsim 1$), presumed to result from convective dredging to the surface of elemental carbon formed by nucleosynthesis inside the star.

Carbonaceous chondrites: A broad class of meteorites, considered to be the least processed meteoritic remnants of the Sun's protoplanetary disk. They are characterized by the presence of chondrules (glassy spherules), together with up to 5% by weight of carbonaceous matter, in a fine-grained matrix. The matrix contains silicates that appear to have been hydrated by the presence of liquid water on asteroidal parent bodies. The carbon is mostly in the form of complex organic polymers and amorphous carbon, but also includes exotic graphite and silicon carbide grains that condensed prior to the origin of the solar system. Amino acids and other prebiotic molecules are also present in trace amounts.

Color index and color excess: A color index is a photometric measure of the color of a star, equal to the difference between magnitudes measured at two specified wavelengths. A common example is $B - V$, where B ("blue") and V ("visual") correspond to passbands with mean central wavelengths of 440 and 550 nm, respectively. Color indices depend on both the intrinsic spectrum of the star and any reddening by foreground dust. The color excess is a measure of reddening, equal to the difference between the observed and "intrinsic" color indices, denoted by $E_{B-V} = (B - V) - (B - V)_0$.

Column density: The number (N) of particles (e.g., atoms, molecules, grains) in a column of unit cross-sectional area, frequently used in astronomical spectroscopy as a measure of the abundance of an absorber toward a radiation source. For a column of length L (equal to the distance of the source), it is related to the number density (n, particles per unit volume) by $N = nL$. The SI unit is m^{-2}; however, the cgs unit cm^{-2} is widely used in the literature.

Cosmic rays: Highly energetic atomic particles traveling at relativistic speeds. Most are protons, but all common atomic nuclei are represented. The primary source is thought to be supernova explosions. Cosmic rays are important in astrochemistry because, unlike energetic photons, they penetrate the interiors of dense molecular clouds, thereby providing an energy source that can instigate chemical reactions.

Depletion: A shortfall in the abundance of a chemical element measured in interstellar gas relative to standard abundances, attributed to its assumed presence in dust grains.

Diamond: A crystalline form of solid carbon in which C atoms are arranged tetrahedrally in a cubic structure, with each of the four valence electrons of a C atom forming a covalent bond to a neighboring atom (sp^3 hybridization).
Early-type stars: Luminous ($L_* \gtrsim 500\ L_\odot$) stars characterized by hot ($T_{\rm eff} \gtrsim 15{,}000$ K) photospheres, including stars of spectral types O and B, and Wolf-Rayet stars. Their distribution in the Milky Way closely follows the galactic disk. Because of their high surface temperatures, early-type stars are primary sources of ultraviolet photons in the interstellar radiation field. They are relatively short-lived and thus typically much younger than less luminous main-sequence stars like the Sun.
Effective temperature: The temperature ($T_{\rm eff}$) of a blackbody that would emit the same bolometric luminosity per surface area as a body such as a star or planet.
Emission nebula: Generic term for a cloud of hot, ionized gas, such as an H II region or a planetary nebula, maintained in an ionized state by radiation from internal or nearby star(s). Their spectra are characterized by emission lines.
Equivalent width: A measure of the strength of a spectral line, defined on an intensity plot as the width of a rectangle with height corresponding to the continuum level and area equal to that enclosed by the line profile; values may be expressed in either wavelength or frequency units, related by $W_\lambda = (\lambda^2/c)W_\nu$. For an unsaturated absorption line, the equivalent width is directly proportional to the number of absorbers in the line of sight.
Flux density: Measure of irradiance per unit wavelength or frequency interval (F_λ or F_ν). These forms are related by the equation $F_\lambda d\lambda = F_\nu d\nu$, hence $F_\lambda = (-c/\lambda^2)F_\nu$. The SI unit of F_ν is W m^{-2} Hz^{-1}; for convenience the Jansky (Section A.1) is generally used. The preferred unit for F_λ is W m^{-2} μm^{-1}. See also *Surface brightness*.
Glasses with embedded metal and sulfides (GEMS): Glassy silicate minerals found in anhydrous interplanetary dust particles, probably formed by condensation in the solar nebula and subsequently accreted into comets. Their composition and mineralogy are broadly similar to those inferred for interstellar silicates. GEMS contain Fe-rich subparticles that enhance magnetic susceptibility and could facilitate alignment if present in interstellar dust.
Graphite: A crystalline form of solid carbon consisting of regularly-stacked planar sheets (graphene), each sheet being a two-dimensional lattice of sp^2-bonded carbon atoms arranged in interconnected hexagonal rings. Graphitic nanoparticles may be responsible for a prominent absorption feature centered near wavelength 217 nm in the interstellar extinction curve.
HII region: Interstellar matter in which hydrogen gas is maintained in an ionized state by stellar ultraviolet radiation. Compact H II regions occur in dense gas surrounding embedded OB stars. Diffuse H II regions are more extensive and lower in density (see Section 1.3.3).
Hot cores and corinos: A hot core is a compact ($\lesssim$0.1 pc), dense ($n_{\rm H} \sim 10^{12}$ m^{-3}), warm ($\gtrsim$100 K) region around a high-mass young stellar object. This combination of density and temperature favors a rich chemistry, in which sublimation products of ices may feed gas-phase chemical networks to form molecules of greater complexity. A hot corino is a comparable region around a lower-mass YSO.

Hydrogenated amorphous carbon (HAC): A soot-like form of solid carbon with H atoms attached to surface sites (also known as a-C:H). Its structure may be microcrystalline, containing interlinked graphitic or tetrahedral subunits, but lacks long-range order.
Initial mass function (IMF): A measure of the relative number of stars born within an incremental mass range, found observationally to vary approximately in proportion to $M_*^{-2.35}$ for stars of mass $M_* \gtrsim 1\ \mathrm{M}_\odot$.
Interplanetary dust particles (IDPs): Interplanetary particles with diameters typically in the range 1 μm–1 mm. Probable sources include release of dust by comets during solar perihelion passage, and collisional abrasion of asteroids. The smallest IDPs decelerate rapidly on entering the Earth's atmosphere, enabling samples to be collected by aircraft in the stratosphere. IDPs are typically composed of silicates and amorphous or organic carbon, and may be distinguished from terrestrial dust by their structure and isotopic composition.
Interstellar radiation field (ISRF): The internal radiation field of the Milky Way (or other galaxies) resulting from emission by stars, and reprocessing of starlight caused by scattering, absorption, and emission by interstellar dust. The spectral energy density of the ISRF in a given region thus depends on the local distributions of both stars and dust. The energy density integrated over all wavelengths is $U \approx 8 \times 10^{-14}\ \mathrm{J\ m^{-3}}$ in the solar neighborhood.
Kerogen: Insoluble, tar-like organic matter of high molecular weight found in terrestrial sediments; similar in physical and chemical properties to organic matter found in carbonaceous meteorites and to residues synthesized in the laboratory by energetic processing of interstellar ice analogs.
Kuiper Belt: A toroidal disk around the Sun, approximately coplanar with the planetary system, extending outward from Neptune's orbit (30 AU) to about 50 AU. Like the asteroid belt, it consists mainly of small bodies considered to be remnants of the Sun's protoplanetary disk. Its largest members include the dwarf planets Orcus, Pluto, Haumea, Quaoar, and Makemake.
Late-type stars: Stars characterized by relatively cool ($T \lesssim 4{,}500$ K) photospheres. The term is most commonly used to refer to red giants and supergiants that have evolved beyond the main sequence, including both carbon stars (spectral class C) and stars with more typical C:O ratios (classes K and M).
Luminosity class: A component of the stellar spectral classification system used to group stars by luminosity, using a notation based on roman numerals. The five main groups are I (supergiants), II (bright giants), III (giants), IV (subgiants), and V (main sequence).
Magnitude (mag): Logarithmic measure of brightness, based on an ancient visual ranking system, defined such that the magnitude difference between two stars of intensities I_1 and I_2 is $m_2 - m_1 = -2.5 \log(I_2/I_1)$. Hence, an intensity ratio of 100 corresponds to a magnitude difference of exactly 5. Note that magnitudes are numerically greater for dimmer stars.
Main sequence: The most stable phase of a star's evolution, in which energy is produced by core hydrogen burning.

Metallicity: A measure of the heavy-element content of an astrophysical system such as a star, nebula, or galaxy. All condensible elements of atomic weight $\geqslant$12 (carbon and above) are generally considered to be "metals" in this context. Often expressed on a logarithmic scale relative to solar abundances, using Fe as a reference element (see Equation (7.1)).
Nanoparticles: A generic term for ultrafine particles, typically defined as those with diameters in the approximate range 1–100 nm. A more restrictive range of 1–10 nm is adopted in the present text, such that the largest remain in the small-particle limit (Section 2.1.2) for extinction calculations at the shortest wavelengths ($\lambda \sim 100$ nm) covered by the observations. Individual large molecules such as PAHs are not usually considered to be nanoparticles although they may overlap in size.
Nova: A stellar outburst caused by explosive thermonuclear ignition of matter in the outer layers of a white dwarf in a close binary system, triggered by mass transfer from its companion star. Unlike the corresponding class of *supernova* (a type Ia SN also involves a white dwarf in a close binary system), a nova event does not destroy the progenitor and can recur periodically. The explosion ejects matter from the system. Evidence for dust condensation in the expanding envelopes of some novae is provided by the onset of a period of intense infrared emission, accompanied by a drop in visual brightness caused by extinction.
OB association: A large, young star cluster in which the most luminous members are OB stars, resulting from star formation in a giant molecular cloud.
OB stars: Generic term for stars of spectral classes O and B, often used in studies of interstellar extinction and element depletions (Section 3.1 and 7.2); see also *Early-type stars*.
OH/IR stars: Oxygen-rich post-main-sequence stars that have developed optically-thick dust shells as a consequence of rapid mass loss during late phases of evolution on the *asymptotic giant branch*. Their primary observed characteristics are OH maser line emission at radio wavelengths and intense continuum emission from circumstellar dust in the infrared.
Oort cloud: A hypothetical spheroidal cloud of icy bodies surrounding the solar system at radial distances in the approximate range 10^3–10^5 AU (from beyond the heliosphere to distances approaching the nearest stars), introduced to explain the orbital characteristics of long-period comets. Its members could not have formed at such large distances from the Sun; their current distribution is attributed to scattering by gravitational interactions with the giant planets.
Optical depth: A measure of the attenuation of radiation passing through a medium, defined by the equation $\tau = \ln(I_0/I)$ where I_0 and I are initial and observed values of intensity. A medium is said to be optically thick if $\tau \gg 1$ and optically thin if $\tau \ll 1$. The extinction in magnitudes is directly proportional to the optical depth at the corresponding wavelength ($A_\lambda = 1.086\tau_\lambda$).
Organic refractory matter (ORM): Complex, non-volatile organic matter synthesized in the laboratory by ultraviolet photolysis or energetic ion-bombardment of ices containing molecules thought to be present in molecular clouds and comets (also known colloquially as "yellow stuff"). It has a non-specific composition that typically includes randomly-linked aromatic and aliphatic subunits, similar to

naturally-occurring insoluble organic matter (kerogen) found in carbonaceous meteorites and terrestrial sedimentary rocks.

Planetary nebula (PN): Expanding cloud of hot (~10,000 K) ionized gas ejected from a central star (so-called because some spherically-symmetric examples resemble planets in visual appearance). The progenitor is a star of intermediate initial mass (~0.8–8 $M_\odot$) that has reached the *asymptotic giant branch* of the HR diagram. The expanding envelope of the star forms the nebula, and its hot, compact core becomes a white dwarf.

Planetesimals: Solid bodies typically ranging up to a few tens of km in size, formed by accretion of dust and ices in a protoplanetary disk. Comets and small asteroids are considered to be remnant planetesimals from the solar nebula. Planetesimals massive enough to accumulate matter by gravitational forces are termed planetary embryos.

Polycyclic aromatic hydrocarbons (PAHs): A class of organic molecules composed of individual planar sheets of regularly-linked hexagonal carbon rings with peripheral hydrogen atoms attached. The simplest PAH is naphthalene ($C_{10}H_8$), consisting of two linked rings. In principle, there is no limit to the size and two-dimensional structure of PAHs, but compact, stable forms are likely to be favored in the interstellar medium.

Pre-main-sequence (PMS) star: A young stellar object that has commenced energy production by internal nuclear reactions but has not yet reached the main sequence. The term is sometimes used interchangeably with *protostar*; however, pre-main-sequence stars typically have visible photospheres, whereas protostars emit almost entirely in the infrared.

Protoplanetary disk: Rotating equatorial disk of material (gas and dust) around a newly-born star. Low-speed collisions between co-rotating dust particles may lead to accretion, forming planetesimals, and ultimately, planets.

Protostar: A young stellar object powered mainly by gravitational energy released by in-falling matter, prior to the onset of nuclear fusion in its core. A protostar typically emits radiation almost entirely in the infrared region of the electromagnetic spectrum.

R Coronae Borealis (RCB) stars: A class of eruptive variable star, named after the prototype, that shows two distinct modes of variability: (i) a regular, low-amplitude pulsation, and (ii) unpredictable deep declines in brightness, each followed by a gradual recovery. Members of the class are yellow supergiants (spectral type F or G) with atmospheres depleted in hydrogen and enriched in carbon compared with typical abundances. The deep declines in their light curves are attributed to episodes of circumstellar dust formation in their atmospheres.

Reflection nebula: A cloud or region that is rendered visible primarily by scattering of starlight by dust grains. Reflection nebulae are distinguishable from emission nebulae by their blue appearance (e.g., Figure 1.3).

Silicates: Minerals based on linked tetrahedral SiO_4 units. Terrestrial silicates, which make up about 90% of the Earth's crust, are typically crystalline and may include a wide variety of compositions and structures. Interstellar silicates appear to be predominantly amorphous (non-crystalline) and anhydrous (lacking internal OH or

H_2O units), with compositions limited by cosmic abundances to largely Mg-rich and Fe-rich forms. Common groups include pyroxenes (composed of interlocking tetrahedral units with generic formula $Mg_{1-x}Fe_xSiO_3$, where $0 \leqslant x \leqslant 1$) and olivines (isolated units linked by interstitial cations, generic formula $(Mg_{1-x}Fe_x)_2SiO_4$). The "end-members" of these groups ($x = 0$ or 1) are enstatite ($MgSiO_3$), ferrosilite ($FeSiO_3$), forsterite (Mg_2SiO_4), and fayalite (Fe_2SiO_4).

Solar nebula: The cloud of gas and dust from which our solar system formed.

Spheroidal particles: A spheroid is a shape obtained by rotating an ellipse around one of its axes, said to be oblate for rotation about the minor axis and prolate for rotation about the major axis. In either case, the particle has an axis of symmetry corresponding to the axis of the ellipse, and a shape specified by the axial ratio b/a. Spheroidal particles are often assumed in numerical models for interstellar polarization. A spheroid is a special case of an ellipsoid, which presents an elliptical cross section about each of three orthogonal axes.

Starburst: A starburst region in a galaxy is a region of exceptionally rapid current star formation activity, attributed to gravitational collapse and fragmentation of a giant molecular cloud. A starburst galaxy is one undergoing an episode of widespread star formation activity, generally attributed to compression of its interstellar matter as the result of a merger or tidal interaction with a neighboring galaxy.

Stardust: Dust formed by condensation in the atmosphere or ejecta of a star. Likely sources include the winds of red giant and supergiant stars, especially those on the asymptotic giant branch, and cataclysmic events such as nova and supernova explosions. Stardust particles that formed prior to the origin of our solar system have been detected in meteorites by isotopic analysis. The term was also adopted to name a space mission, operational 1999–2011, designed to collect and return samples of cometary and interstellar dust.

Stoichiometry: A term used to describe quantitative relationships or ratios between two or more elements within a substance resulting from chemical reactions. For example, magnesium silicates can form as distinct compounds, enstatite ($MgSiO_3$) or forsterite (Mg_2SiO_4), that have differing abundance ratios between the constituent elements.

Supernova (SN): Catastrophic explosion of an aging star at the end of its life. Supernovae (SNe) are triggered in one of two ways: accretion by a white dwarf from a companion star in a close binary system to reach a critical mass for thermonuclear runaway (type Ia), or gravitational core-collapse in an individual, massive star (types Ib, Ic, and II). SNe are the primary sources of many of the heavier chemical elements in the universe, and they also produce cosmic rays and shock waves that permeate the interstellar medium. The adopted terminology denotes the year and alphabetical order of discovery; e.g., SN 1987A was the first supernova event to be observed in 1987.

Supernova remnant (SNR): The rapidly expanding cloud of hot gas emanating from a supernova explosion.

Surface brightness: A measure of intensity per unit wavelength or frequency interval per unit solid angle of the radiation received from an extended source such as a

nebula or circumstellar disk. The flux density received in a beam of solid angle Ω in a direction (θ, ϕ) is

$$F_\nu = \int I_\nu(\theta, \phi)\, \mathrm{d}\Omega$$

where I_ν is the surface brightness in W m^{-2} Hz^{-1} sr^{-1}. If the beam is smaller than the scale for variations in I_ν, then $F_\nu \approx I_\nu \Omega$. The wavelength form I_λ (W m^{-2} μm^{-1} sr^{-1}) is related to the frequency form I_ν in the same way as F_λ to F_ν (see *Flux density*).

T Tauri stars: Young (pre-main-sequence) stars of low to moderate mass, named after a prototypical example. The Sun is presumed to have passed through a T Tauri phase prior to becoming a main-sequence star.

Wien's displacement law: The wavelength of the peak intensity of radiation emitted by a blackbody is inversely proportional to its temperature: $\lambda_{\mathrm{peak}} = b/T$ where $b \approx 2989$ μm K is a constant. A modified form (Equation (2.47)) applies to an infrared source represented by the product of a blackbody spectrum and a power-law emissivity function.

Young stellar object (YSO): Generic term for stars in their early stages of evolution, including protostars and pre-main-sequence stars.