1

Cosmic Structures

In this first chapter, the *cosmic players* (objects) are introduced superficially, whose detailed properties will then entertain us to the end of the book. The play starts in front of our doors, with the Solar System, and continues to our host galaxy, the Milky Way, and further to groups and clusters of galaxies until the outer reaches of observation, the Early Universe. Emphasis will be placed on length scales, time scales, masses, velocities, densities, temperatures, pressures, magnetic fields, and radiations. The newcomer can find more facts and observational backup, e.g., in [Karttunen et al., 2000].

1.1 Calculus and Notation

Astrophysics differs from other branches of physics by its difficult accessibility. A deficit of tangible and visible detail must be replaced by a surplus of imagination and cross-linkages, and *interpretations* require many more order-of-magnitude estimates than otherwise for which precision is less important than speed and transparency. Success in research thus depends more critically on a handy calculus.

As in every new field of physics, familiarising with the relevant *scales* is of paramount importance. For instance, civilized people are quite familiar with velocities of order several km/h or with temperatures of the order of 30°C, because we have memorised typical hiking, cycling, and driving speeds, and typical temperatures like freezing, and evaporating of water, room temperature, and body temperature. For me, the difficulties start already when I am asked for my temperature in units of Fahrenheit: switching to another system of units requires memorising the (usually linear) conversion rules, and is, in principle, avoidable. One system of units suffices for all of physics.

As such a preferred system, this book will use the *Gaussian cgs system*, because it avoids the conversion factors ϵ_0 and μ_0 accompanying electric and magnetic field strengths. Is there an objectively preferred system of units? The answer is "no": in principle, there are as many physical dimensions as

different physical measurement setups, i.e. very many. But as most of them measure equivalent sets of numbers – as a consequence of laws of nature – they have been eliminated, and expressed in terms of earlier ones. Every law of nature permits the elimination of one dimension, until, in the end, all dimensions are again removed, in the *natural system* of units which involves the universal constants c, G, and $\hbar$. In this natural system, the fundamental quantities length, time, mass, (rest) energy are expressed in terms of those of a Planck particle, of mass $M = \sqrt{\hbar c/G} = 10^{-4.7}$g, and (Compton wave-) length $10^{-34.8}$m. But such a dimensionless description of nature would have disadvantages: Not only would we have to memorise rather unfamiliar (large or small) numbers; we would, above all, lose the most useful dimensional test which greatly facilitates detecting errors, and which even helps in finding new formulae. For these reasons, cgs units have carried through, by realising a useful compromise.

Calculations can be done in awkward and non-awkward ways. A clever way is used by arithmetic artists who perform difficult calculations by heart: they multiply *logarithmically*, and thereby deal with fewer figures. Example: the fourth root of 390625 equals $10^{5.6/4} = 10^{1.4} = 25$, whereby $\log 4 = 0.6$ and $\log 2.5 = 0.4$ have been used, at an accuracy of a few per cent. Higher accuracies can be obtained by using a calculator.

Logarithmic calculations flourished during the era of the slide-rule, and of the tables of natural and decadic logarithms. They suggest the following *index notation* of quantities and formulae, which is widely used but hardly ever systematically so:

$$A_x := A/10^x \dim(A) , \tag{1.1}$$

where A is a physical quantity of dimension $\dim(A)$. Example: $v_7 = v/10^7$cm s^{-1}; i.e. v_7 is a dimensionless number, viz. the velocity v expressed in units of 10^7cm s$^{-1} = 10^2$km/s, (which occurs frequently in the Universe).

As an advanced example of the conciseness and usefulness of the index calculus, let us anticipate formula (5.5) for the temperature dependence of the electric conductivity σ of a sufficiently dense hydrogen plasma: $\sigma_{14} = T_4^{3/2}$; in words: σ amounts to 10^{14}s^{-1} for a plasma temperature T of 10^4K, and grows with T as $T^{3/2}$. Another example is the connection between temperature and sound speed for a hydrogen gas, (1.10): $c_8 = \sqrt{T_8}$.

Powers of ten are alternatively expressed by prefixes, like {D, H, K, M, G, T, P, E} for 10^n with $n = \{1, 2, 3, 6, 9, 12, 15, 18\}$, and {d, c, m, μ, n, p, f, a} for 10^{-n}. Unfortunately, the AIP Style Manual deviates from above by using "da, h, k" instead for the first three enlargement prefixes, "da" for "deka"; Springer Company has urged me to follow this ugly convention in the present edition.

1.2 Solar System

Let us start our excursion around the Universe at our front door, so to speak, with our Solar System. Our planet Earth has a radius $R_\oplus = 10^{3.8}$km $= 10^{8.8}$cm. It encircles the central star, the Sun – of spectral type G2, mass $M_\odot = 10^{33.3}$g – at a distance of one *astronomical unit* AU $= 10^{13.17}$cm or 8 light minutes, at the Keplerian speed

$$v_\oplus = \sqrt{GM/r} = 10^{(-7.2+33.3-13.2)/2}\text{cm/s} = 10^{6.5}\text{cm/s} = 30 \text{ km/s} , \quad (1.2)$$

a speed which is known to correspond to a revolution period of one year $= 10^{7.5}$s. As a consequence of this motion, all celestial bodies (planets, nearby stars) perform small ellipses on the celestial sphere. The almost constant solar distance ($d = $ AU) implies that we receive from the Sun an almost constant energy flux (= radiation power per area) $S_\odot$, given by

$$S_\odot = L_\odot/4\pi d^2 = 10^{33.6-1.1-2\times13.2}\text{erg/cm}^2\text{s} = 10^{6.1}\text{erg/cm}^2\text{s} , \quad (1.3)$$

or $S_\odot = 10^{3.1}$W/m^2, the so-called *solar constant*; of which we have known since the late 1990s that it partakes in the 11-year-period solar magnetic oscillation (or rather: (22.2±2)-yr period), with an amplitude of 0.1%, in phase with the sunspot number and with various other solar properties. (A reduction of radiation power in the spots is overcompensated by an increase from around them.) Here, the solar luminosity $L_\odot$ has been evaluated from

$$L_\odot = 4\pi R_\odot^2 \sigma_{SB} T_\odot^4 = 10^{1.1+2\times10.8-4.2+4\times3.76}\text{erg/s} = 10^{33.6}\text{erg/s} , \quad (1.4)$$

with the Stefan-Boltzmann constant σ_{SB} listed in the table of 'useful numbers' on page XIII.

The Sun formed 4.6 Gyr ago, more or less simultaneously with its planets. We think that in this process, an angular-momentum excess of the contracting gas cloud caused the transient formation of a flat, proto-planetary disk whose particles revolved differentially and thereby exerted shear forces onto each other such that they gradually spiraled inward toward the disk's core, the forming Sun. In more detail, gas, dust, and larger condensations will have separated from each other, condensed and evaporated, and spiraled inward at different rates because of varying amounts of pressure support. The proto-planetary disk acted like a grand ultra-centrifuge and thereby provided the conditions for the formation of *planets* and their *moons*, with their different chemical compositions which show a monotonic dependence (e.g. of evaporation temperature) on solar distance. (Whereas the Universe consists primarily of hydrogen, the Earth's mantle consists primarily of silicon and oxygen, at comparable weights, its core dominantly of iron, and carbon is strongly underabundant). At the disk's center formed the young Sun, initially with the (minimal) rotation period of 3.6 h.

Such a high initial spin of the Sun appears to conflict with a backward extrapolation of its present spin period, of (27.3 ± 0.5)d, if evaluated

from the present braking rate, the latter estimated from its mass loss $\dot{M}$ $= -10^{-14} M_\odot/$yr via the *solar wind*. Uncertain in this estimate is the effective lever arm out to which the Sun forces its wind into (rigid) corotation: If that lever arm was as large as $30 R_\odot$, $(R_\odot = 10^{10.8}$cm) – as repeatedly claimed by Lotova [1988] – i.e. some 10^2 times the solar inertia radius ($\approx R_\odot/3$), the present spindown rate would be as large as $\dot{J}_\odot = -10^{-10} J_\odot/$yr, and a large spin at birth would no longer appear implausible. Independently of this rather uncertain estimate, a formation of the Sun at the center of its accretion disk argues in favour of a maximal initial angular momentum, because gravitational and centrifugal forces should have balanced at its rotational equator, as on a Keplerian orbit.

A further, independent hint at a high initial spin of the Sun comes from the insight of the 1980s that, quite likely, all newborn stars pass through the *bipolar-flow* stage – whereby *all* is maintained with the uncertainty inherent in every statistical statement – during which a star blows two antipodal supersonic jets into its circumstellar medium, parsecs long, at right angles to its accretion disk. The precise mechanism of blowing has remained controversial until today, but most authors make strong magnetic fields and high rotational velocities (of disk and/or star) responsible for its functioning; see Chap. 11. The bipolar-flow stage lasts some $10^{4.5}$yr, estimated from the age of the oldest stellar jet sources, and brakes the central (pre T-Tauri) star. The bipolar-flow energy is limited by the star's initial rotational energy.

Let us return to the Sun which, in its core, has burnt hydrogen to helium for 4.6 Gyr at an almost constant though slightly increasing burning rate (due to an increasing mass density there), as a so-called *main sequence* star, and radiates the thus-liberated nuclear energy at its surface at a (photospheric) temperature of

$$T_\odot = 5.77 \text{ kK} = 10^{3.76} \text{K} \tag{1.5}$$

into space, see Plate 1. At the same time, it blows the solar wind, first inferred from the existence of (two branching) cometary tails, and later from magnetospheric storms which succeed visible eruptions on the surface within $\gtrsim$ two days. The solar wind blows unsteadily, at velocities between $10^{2.3}$km/s and $10^{3.3}$km/s, usually between 4×10^2 und 8×10^2km/s, whereby the lower values prevail at equatorial latitudes, the higher values at polar ones. It presses against, or confines the *interstellar medium* (ISM) of the Milky Way, out to a distance of at least $10^{10.3}$km $= 10^{2.1}$AU which has not yet been reached by the American Pioneer and Voyager spaceships (launched during the 1970s, and escaping at speeds, after swing-by, of 3.5 AU/yr; d(Pioneers) $\leq 10^{10.08}$km on 27 April 2003 [Nature 426, 45]). The solar mass loss dominates (presently) at low solar latitudes.

The position and structure of the edge of the *heliosphere* – the inner bowshock towards the ISM, or *termination* shock, and the heliopause, or *stagnation* surface – depend on the composition of the ISM and on whether its relative velocity, of some 25 km/s, means super- or subsonic motion; see

Sect. 2.3. Conservatively, this ISM is conceived of as *warm* hydrogen, of (ionization) temperature 10^4K. Instead, it may consist of relativistic electrons and positrons, so-called *pair plasma*, which should be generated abundantly in coronal magnetic-field reconnections around compact and normal stars and which has revealed its omni-presence in the Milky Way through the (mapped!) 511 keV annihilation radiation and, indirectly, through a missing factor of 5 of sufficient warm hydrogen [Reynolds, 1990; eV $= 10^{-11.8}$erg]. The heliopause would be open in the first (supersonic, stretched) case but closed (ellipsoidal) in the second case. Whatever this tenuous medium, the solar wind screens its planets against it, also against the soft tail of the so-called *cosmic rays*, a highly relativistic plasma of probably Galactic origin, see Chap. 10.

Earth screens itself against the solar wind by its *magnetosphere*, of radius $\gtrsim 10R_\oplus$, which diverts it (because of its high electric conductivity). The *magnetotail* of Earth reaches far beyond the lunar orbit; it scans the moon at monthly intervals. Earth is probably the only animated planet of the Solar System because it is the only planet whose typical (surface) temperatures have always ranged between 0°C and 100°C, i.e. allowed for liquid water. Note that a once-frozen Earth would hardly have thawed again, because of the high albedo of ice and snow, and correspondingly a once-dried-up Earth would never have formed rivers, lakes, and oceans again, because of its low albedo: thermal Earth has managed to pass between both Skylla and Charybdis. Its solar distance realizes the optimal distance, within a few per cent, of an always wet planet, on which life appears to depend [Rampino and Caldeira, 1994].

As is well known, the Solar System contains eight or more additional planets whose solar distances obey, approximately, the rule of *Titius* and *Bode*: $d_n/\text{AU} = 0.4 + 0.3 \times 2^n$, $n = -\infty, 0, 1, 2, ...$, where $n = 3$ counts the position of the asteroid belt (or gap) between Mars and Jupiter. A simpler, and even better fit is the pure exponential law: $d_m/\text{AU} = 0.2 \times (\sqrt{3})^m$, $m = 1, 2, 3, ...$ It is presently unknown whether or not *other planetary systems* obey the same rule; those detected tend to contain higher-than-Jupiter masses on inner-planet orbits, and to have more eccentric orbits. Of general validity may be the approximate logarithmic equi-distribution, characterized by the factor $(\sqrt{3})^m$. Note that these rules do not make a prediction about the expected masses, and chemical compositions: Whereas the outer planets, starting with Jupiter, have near-solar compositions, the inner ones are strongly enriched with (above all) stony and carbonaceous material as well as iron alloys. Only in this way does Homo Sapiens find the ≈ 40 different chemical elements required for his functioning, see Fig. 1.1.

Besides the planets, the Solar System lodges their moons which may have formed in a similar way from orbiting accretion disks left over after the planets had formed from the main disk, by (first) chemical and (then) gravitational coagulation. This convincing mechanism has been cast into doubt recently for 'our' own moon – in favour of a catastrophic ejection via a gigantic collision – because backward integration of its tidal interaction with Earth brings it closer to it, with increasingly stronger tides in the past. How close to Earth
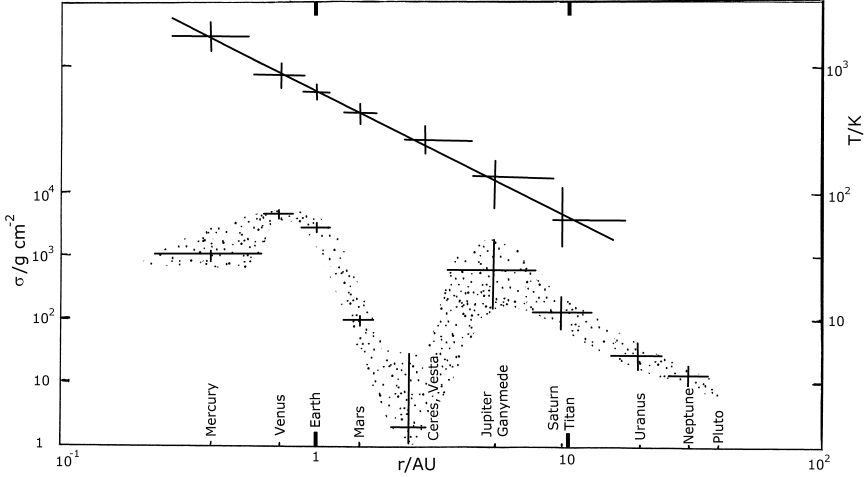
Fig. 1.1. Sketch of the inferred smoothed minimal mass distribution per area $\sigma(r)$ in the Solar System, and of the evaporation temperature $T(r)$ of the main constituent substances of listed planets, moons, or asteroids, both as functions of radial distance r measured in astronomical units. The 'minimal mass' has been obtained from the observed mass by replacing the 'missing' hydrogen and helium under the assumption of solar-system abundances. The mass distribution appears two-humped. All temperatures are consistent with the drawn-in law $T_2 = 1/r_{14}$

was the moon born? How fast did Earth spin then? Its initial spin must have sufficed to expand the lunar orbit towards its present size, in addition to tidal losses on the Sun, and magnetic friction on the solar wind. On the other hand, collisional kicking ignores the difficulty of ejecting mass from a celestial body without subsequently re-absorbing it, after a certain number of intersecting orbits. The Solar System is an inexhaustible playground for physical exercises! More about it can be found in Sect. 13.8.

Still it should be mentioned that besides the planets and moons, the Solar System contains comets and asteroids of icy, carbonaceous, stony, and iron-rich composition, as well as smaller bodies and dust made of the same materials. Most of the *asteroids* are found in the 'gap' between Mars and Jupiter, whilst most of the *comets* may have formed beyond Pluto, in the *Kuiper belt*, at $40 \lesssim d/AU \lesssim 130$, and may have been ejected, via binary encounters, into the much larger, quasi-spherical *Oort reservoir*, at $d \lesssim 10^{5.3} AU$.

Remarkably, the *mass distribution* $\dot{N}(M)$ of the flow rates of all solar-system bodies, determined both via in situ measurements by spacecraft and via crater statistics on the moon, is an approximate power law, all the way from molecules up to the asteroids, given by:

$$M^2 \dot{N}_M = 10^{-19\pm2} \, g/cm^2 s \quad \text{for} \quad 10^{-18} \lesssim M/g \lesssim 10^{18} \tag{1.6}$$

with $\dot{N} := dN/dt$, $\dot{N}_M := \partial \dot{N}/\partial M$.

Problems

1. Kepler's law for a circular orbit, $v^2 = GM/a$, relates the sum of the masses $M_1 + M_2 =: M$ to their separation a and their revolution period $P =: 2\pi/\Omega$, $\Omega = v/a$. Find the *revolution times* of two celestial bodies as functions of M and a. What is the minimum P for two balls of equal mass $M_\odot$ and mean mass density $\rho/\mathrm{g\,cm}^{-3} = \{1, 10^6, 10^{15}\}$, respectively – i.e. for {stars, white dwarfs, neutron stars} – whereby $a \geq R_1 + R_2$, $(R_j = \mathrm{radii})$?

2. What *radius* $R(M, \Delta t; T)$ needs a *star* of mass M in order to radiate a fraction $\epsilon = 0.1\%$ of its rest energy during the time interval Δt at the surface temperature T of the Sun? Of particular interest are solar values: $M = M_\odot$, $\Delta t = 10^{10}\mathrm{yr}$.

1.3 The Milky Way

The Solar System is located near the midplane of the (cloudy) Disk of the Galaxy – or Milky Way, a *spiral galaxy* of Hubble type Sb – at a separation of ≈ 20 pc from the midplane, and at a separation of 7.94 kpc from its rotation center [Reid, 1993, Genzel et al, 2003; 1 parsec $= 3.26$ lightyears $= 10^{18.49}$cm]. Here it should be stressed that the Galactic Disk is not plane, rather warped, at angles of $\lesssim 20°$ on length scales $\lesssim$ kpc [Spicker and Feitzinger, 1986]. The local warp is well-known as *Gould's belt* – which contains the gas clouds and the young stars – though this interpretation is often traded for some unexplained explosion, of range 0.5 kpc. Its warping is the reason why the Milky Way forms a broad band in the night sky, rather than a narrow line. Even so, the midplane of the Disk is well defined locally by the (cold, heavy) molecular clouds, of average scale height some 50 pc (typical of the inner part of the Galaxy, rather than of the solar circle); see Fig. 1.4 and Plate 10.

Masswise, the Milky Way consists at 90% of *stars*, of masses between 0.07 and 60 $M_\odot$, and luminosities mainly between $10^{-5}L_\odot$ und $10^2 L_\odot$, yet with record values up to $10^7 L_\odot$, see Fig. 1.2. Only 10% of the mass is presently in the gas phase. The gas is *warm* and shines at some 10^4K – the ionization temperature of hydrogen – whenever heated (and partially ionized) e.g. by nearby stars; if poorly heated, we observe the gas as *cold-HI regions* of approximate temperature 10^2K – in particular in the light of the 21-cm radiation (of nuclear spinflip of H) – or as yet colder *molecular clouds*, of approximate temperature 10 K.

The Solar System revolves around the center of the Milky Way at a velocity of $v_\odot = 2.2 \times 10^2$km/s, corresponding to a revolution period of $P = 2\pi R/v_\odot = 10^{0.8+22.4-7.3}$s $= 10^{15.9}$s $= 10^{8.4}$yr and an enclosed Kepler *mass* of $M = r_\odot v_\odot^2/G = 10^{22.4+2\times7.35+7.2}$g $= 10^{44.3}$g $= 10^{11}M_\odot$. Here it should be stressed that the Kepler law is strictly valid only for spherically symmetric mass distributions; but the overestimate, resulting for an extreme
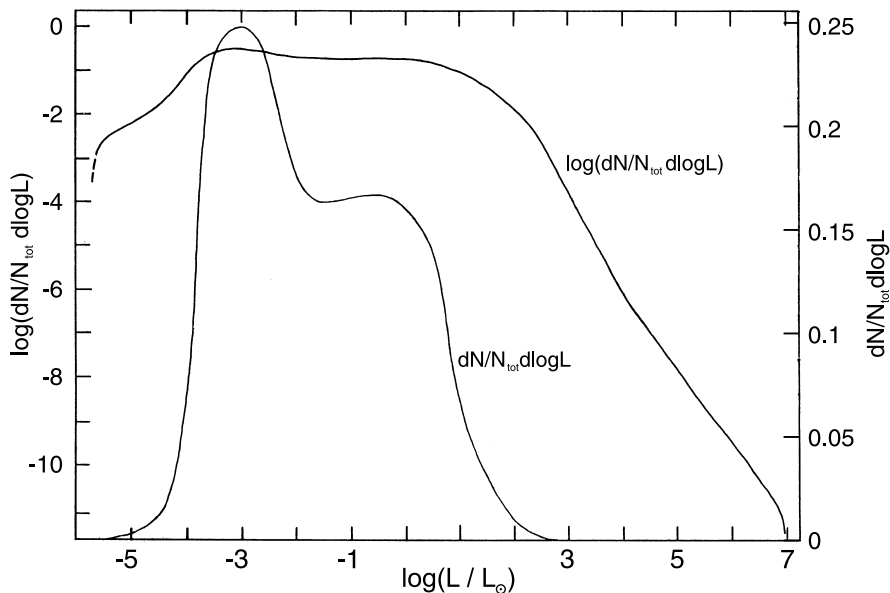
Fig. 1.2. Stellar Luminosity Function (of the local group of galaxies): plotted is the number of detected stars per logarithmic luminosity interval, $dN/N_{tot} d\log(L/\mathrm{L}_\odot)$ vs $\log(L/\mathrm{L}_\odot)$, both linearly (right scale), and logarithmically (left scale). Only a small percentage of stars has luminosities larger than our Sun; such stars are shorter lived, hence have a larger time-integrated share in the population history of our Galaxy; cf. Fig. 8.2

disk-like mass distribution, amounts to less than a factor of 3. Stellar members of the Galaxy have been seen out to 60 kpc from its center; such a large (Galactic) volume may contain as much mass as $10^{12}\mathrm{M}_\odot$. Our Milky Way thus belongs to the large galaxies in the Universe, for a mass distribution ranging between $10^7\mathrm{M}_\odot$ and $10^{14}\mathrm{M}_\odot$ per galaxy.

Conspicuous inhabitants of the Galactic Disk, besides stars, are luminous gaseous clouds – so-called *nebulae* – which are irradiated by nearby, hot stars, or energized by their supersonic expansions: HII regions, planetary nebulae, and supernova remnants (= SNRs). They differ from each other particularly in their spectra, both continuum and emission lines. There are also (massive) *dark clouds*, less irradiated, visible only at much lower frequencies.

Less spectacular are the (already mentioned) *cosmic rays*, an extremely relativistic plasma in apparent pressure equilibrium with the normal gas – or rather plasma – which apparently pervades the whole Milky Way, with ion energies starting slightly below rest energy and ranging all the way up to $10^{20.5}$eV, corresponding to Lorentz factors of $\gamma \lesssim 10^{11.5}$ for protons, a huge energy for an elementary particle, see Fig. 1.3. There is also a leptonic component of the cosmic rays consisting of both electrons and positrons, which
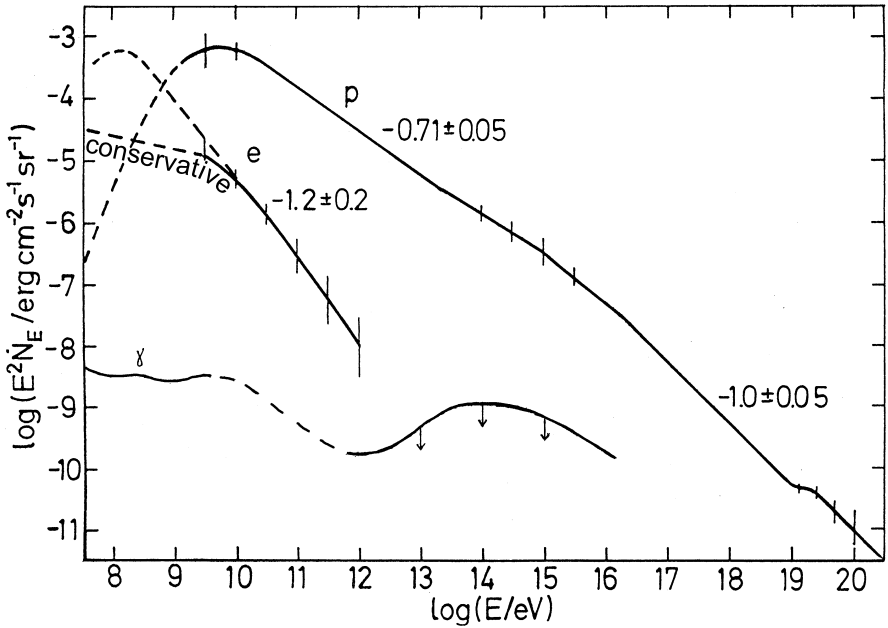
Fig. 1.3. Near-Earth Cosmic-Ray energy spectra, $log(E^2\dot{N}_E)$ vs $logE$, for (dominantly) protons p, electrons e, and photons γ, with spectral indices and typical error bars indicated. At low particle energies, an attempt has been made to eliminate the 11yr modulation by the solar wind. The 'conservative' electron branch assumes their homogeneous distribution throughout the Galaxy whereas the upper branch corresponds to the Milky Way being supported by pair plasma (whose bremsstrahlung is suppressed by being largely excluded from clouds)

involves perhaps a comparable amount of total energy, though distinctly less flux at high particle energies ($\gtrsim$ GeV, as opposed to particle Lorentz factors). When observers draw spectra in which the leptonic component is less energetic than the hadronic one, they assume a one-fluid structure of the Milky-Way plasma; such plots are not directly based on measured fluxes near Earth (for low electron energies), i.e. they depend on additional assumptions, and should therefore carry large (systematic) error bars. Moreover, the cosmic-ray transfer through the heliosphere ought to be charge dependent, because of the higher rigidity pc/Ze of the (positive) ionic component; we lack direct information.

Among the inconspicuous inhabitants of the Galactic Disk range also the ubiquitous *magnetic fields*, of typical field strength 5 μG, hence of comparable pressure to the gas: $B^2/8\pi = 10^{-2\times5.3-1.4}\mathrm{dyn/cm}^2 = 10^{-12}\mathrm{dyn/cm}^2$. They are about 50% ordered, almost parallel to the spiral arms.

What medium fills the Milky Way? This medium is commonly thought to be hydrogen, as the most abundant element in the Universe. But Reynolds [1990] finds a column density of warm hydrogen at most 20% of what would

fill the available volume. Colder components ought to be denser (for supporting their ambient pressure) and could thus be observed, in (cold) emission or absorption. What about hot hydrogen, of temperatures between 10^5K and 10^7K? Arguments against contain the radiation temperatures which vary strongly from one line-of-sight to the next; apparently, such radiation comes from localised overpressure islands of small extent, like HII regions. Moreover, we shall find below that temperatures T between 10^4K and 10^8K are unstable, i.e. that matter with such temperatures either cools quickly, towards 10^4K, or continues heating up, towards $\gtrsim 10^8$K. The *hot* component which fills the Galactic Disk is probably relativistically hot: extremely relativistic *pair plasma*, of typical Lorentz factors γ up to 10^2 and more, jointly with part of the lower-energy ionic cosmic rays (which exert a comparable pressure, are expected to penetrate more deeply into clouds, and which are $10^{3.3}$-times smaller in number); see Fig. 1.4, and Plates 10, 13.

Stars and clouds move relative to each other – in addition to their Galactic revolution – with *velocities* between ≈ 10 km/s and a few 10^2km/s, depending on mass, age, and type. The young, heavy stars, move most slowly, and the neutron stars most quickly (with $v \lesssim 10^{2.7}$km/s, a controversial number which has been once raised, in 1994, by a factor of $\lesssim 4$, based on cases of uncertain distance, much to my worry). Escape velocity from the (potential well of the) Milky Way amounts to $10^{2.7}$km/s. The surface density σ of the Disk's mass has been determined as $\gtrsim 10^{-2}$g/cm^2, corresponding to a typical gravitational field strength $g_\perp$ perpendicular to the Disk of

$$g_\perp = 2\pi G\sigma = 10^{-8}\text{cm/s}^2 \qquad (1.7)$$

at the edge of the Disk; (for symmetry reasons, $g_\perp$ passes through zero in the middle of the Disk). Consequently, all objects oscillate perpendicular to the Disk, with a *scale height* H of

$$H \approx v_\perp^2/2g_\perp = 10^{14-0.3+8}\text{cm } v_7^2 = 0.7 \text{ kpc } v_7^2 \qquad (1.8)$$

for vertical velocities in units of 10^2km/s. For a gas of temperature T, the hydrostatic scaleheight in the same gravity field measures:

$$H = kT/mg_\perp = 10^{-15.9+6+23.8+8}\text{cm } T_6 = 3 \text{ kpc } T_6 \ , \qquad (1.9)$$

i.e. wants temperatures larger than 10^7K to fill the Galactic Halo. Gas below (a kinetic temperature of) 10^6K is gravitationally bound to the Disk, into a thin layer.

Velocities ought to be judged in relation to the respective *sound speed* c_s, i.e. the average speed at which molecules, atoms, or ions move locally. When the fluid medium obeys the adiabatic equation $p \sim \rho^\kappa$, with adiabatic index $\kappa = c_p/c_v = 1 + 2/f$ equal to the ratio of the specific heats at fixed pressure and volume (where $f :=$ number of degrees of freedom), c_s is known to obey:

$$c_s = \sqrt{dp/d\rho} = \sqrt{\kappa p/\rho} = \sqrt{\kappa kT/m} \overset{H}{=} 13 \text{ km/s}\sqrt{T_4(m_p/m)} \ , \qquad (1.10)$$

$$\frac{T_{kin}}{T} = \begin{cases} \lesssim 10 & \text{, molecular clouds} \\ 10^2 & \text{, HI regions} \\ 10^4 & \text{, 'warm' component} \\ \gtrsim 10^7 & \text{, halo plasma} \\ 10^{13} & \text{, pair plasma} \end{cases}$$

T/K = 2.728 , background

10^2 pc

M   M

$$\frac{v}{kms^{-1}} = \begin{cases} \gtrsim 10 & \text{, peculiar of stars; clouds} \\ \lesssim 10^{2.5} & \text{, old stars} \\ \approx 10^{2.3} & \text{, rotation} \\ 10^{2.7} & \text{, escape} \end{cases}$$

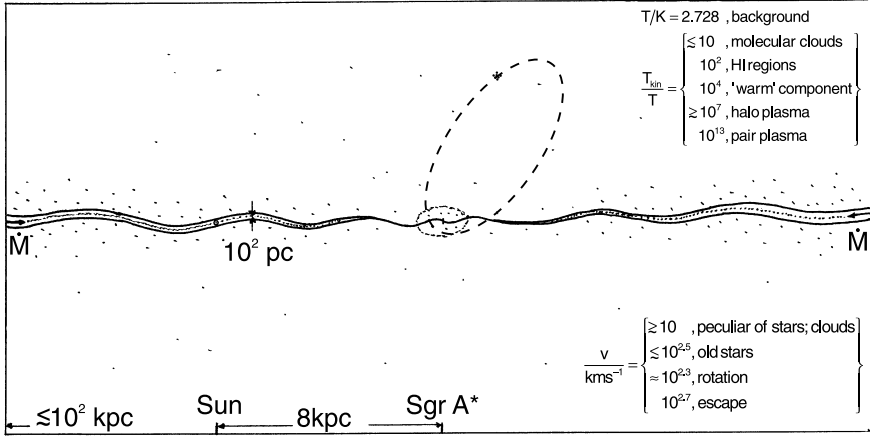≤10^2 kpc   Sun   8kpc   Sgr A*

Fig. 1.4. Sketch of the inferred geometry of the Milky Way as seen from far away in the Galactic plane. Gas and dust of the Disk have a relative scale height of (only!) 1%, but warping makes the disk appear much thicker in projection. All population-I constituents, stars and clouds, oscillate through the disk, due to non-zero kinetic temperatures, whilst population-II objects (globular clusters, Schnelläufer stars) move along highly eccentric orbits with much larger amplitudes. Gaseous matter is inferred to spiral in towards the center, at a rate of $\dot{M} \lesssim M_\odot/yr$. Typical steady 'inhabitants' – beyond stars and clouds – are HII regions, supernova remnants, planetary nebulae, and synchrotron nebulae. The cosmic rays may escape from the disk through several 10^2 narrow 'chimneys'. Typical temperatures are 10^4K (of the 'warm' component), 10^2K (of HI), 10 K (of molecular clouds), $\gtrsim 10^7$K (of dilute halo plasma), and 10^{13}K (of pair plasma), all embedded in the 2.725 K cosmic background. All temperatures but the last are (only) kinetic temperatures. Typical velocities are between 10 km/s and $10^{2.5}$km/s of stellar and cloud peculiar motions, and $10^{2.3}$km/s of (ordered) Galactic rotation at not-too-small radial distances (of $\gtrsim 0.5$ kpc). See also Plate 10

Caption of Plate 10: Our Milky Way seen in ten different frequency ranges, from long-wavelength radio frequencies ($10^{8.6}$Hz) to hard γ-rays (of photon energy $\gtrsim 0.3$ GeV), covering more than 14 orders of magnitude. The individual maps present stripes around the Galactic equator, centered on its rotation center (Sgr A), of width $\leq \pm 10°$ in latitude, but unlimited in longitude ($\leq \pm 180°$). Except for the optical map, colours code either for intensity – ranging from deep blue through green, yellow, and red to white – or they are false colours, using blue, green, and red for three successive intervals of decreasing frequency. Successively from top to bottom, the ten maps tell us the following: **1) LF radio (**near 408 MHz**):** In this LF radio continuum, we see mainly synchrotron radiation from relativistic electrons. Outstanding compact sources are spiral arms and SNRs, most notably Cas A, Vela, Puppis A, and the Crab. **2) atomic H** ($\lambda = 21$cm): At this emission line, we see cold and warm (atomic) hydrogen, concentrated in the (narrow) Galactic cloud layer. **3) HF radio** ($\lesssim 3$ GHz): At this higher-ν radio continuum, we see hot gas (plasma) and relativistic electrons at higher resolution than in 1). The bright, narrow 'ridge' of 1) has been subtracted, for clarity.

4) molecular H (H_2, traced by CO at $\gtrsim 10^2$ GHz): We see the belt of dense, cold gas clouds in which star formation takes place. **5) mid & far IR** (at $\{12, 60, 100\}\mu m$): We see mainly gas heated by stars. The 'zodiacal light', emitted by dust in the solar-system ecliptic, has been (modeled and) subtracted. **6) mid IR** ($6.8 \div 10.8 \mu m$): Emission mainly from polycyclic aromatic hydrocarbons traces bright stars and PNe. **7) near IR** ($\{1.25, 2.2, 3.5\}\mu m$): These frequencies are hardly attenuated by dust; they map cool, giant stars throughout the Galaxy. **8) optical** ($0.4 \div 0.6\mu m$): Visible light is strongly absorbed by foreground dust; we therefore see glowing gas and stars at distances $\lesssim$ kpc. **9) soft X-ray** ($\{0.25, 0.75, 1.5\}$keV): We see nearby hot plasma, because of dust absorption. Outstanding are the Cygnus Loop, Vela SNR, IC 443, and Crab. **10) γ-ray** ($\gtrsim 0.3$ GeV): Hard γ-rays are emitted when cosmic rays collide with Galactic gas, and also by pulsars. Outstanding are the Galactic Center, the (near) Vela PSR, (very near) Geminga, and Crab. [Courtesy of Dave Leisawitz: NASA Goddard Flight Center]

the last equality for hydrogen (H) at $T = 10^4$K, and with m as the mean particle mass. I like to memorise this result in the short form $c_8 \overset{H}{=} \sqrt{T_8}$; it will find repeated application.

For the warm component of the Milky Way ($T = 10^4$K), speeds of order 10 km/s are thus near sonic whereas for the cold component, sound speed is closer to 1km/s ; for (relativistic) pair plasma, on the other hand, we have $c_s = (2/3)c = 10^{10.3}$cm/s. *Supersonic speeds* are frequent in the Universe – where gravity can act through large distances – whereas they are rare on Earth, occurring (only) in: lightning, in a whip's crack, a supersonic aircraft, rockets, cannons, guns, and bombs.

The composition of the Milky Way's *Halo* is not perfectly known. As calculated above, hydrogen would be a candidate if at $T \gtrsim 10^7$K; yet there is little evidence for such. For the space-filling agent of the Halo, better candidates are the pair plasma which escapes from the (magnetic fields of the) Disk, plus the ionic component of the cosmic rays. They escape on the timescale of $10^{7\pm0.3}$yr – as measured by the lifetimes of their radioactive-decay products as well as by their secondary components – probably through Galactic *chimneys,* viz. small-scale leakages which are realized by escape channels rammed open via the overpressure of dense HII regions. (Remember that diffusive escape of air from an old air mattress can be tolerably slow, whereas such escape is prohibitively fast if due to a tiny puncture). In the escape process, some hot gas is likely to be dragged along, similar to sand storms which do not exclusively consist of warm air.

The *escaping number rate* $\dot{N}$ of relativistic ions should almost equal its generation rate, $\dot{N} = n\dot{V}$, with $n \gtrsim u/\langle\gamma\rangle mc^2 = 10^{-11.8-0.7+23.8-21}cm^{-3} = 10^{-9.7}$cm^{-3} being the average number density of cosmic rays in the Disk, $u \approx$ eV/cm^{-3} = their energy density, $\langle\gamma\rangle =$ their Lorentz factor ≈ 5, $V =$ the occupied Disk volume (assumed box-shaped),

$$V = \pi R^2 H = 10^{0.5+45+20.5}\text{cm}^3 = 10^{66}\text{cm}^3\ H_{20.5}\ , \qquad (1.11)$$

and with the mean storage time $t = 10^7 \text{yr} = 10^{14.5}\text{s}$ entering as $\dot{V} = V/t$, see Fig. 1.5. Consequently:

$$\dot{N} = n\dot{V} = 10^{-9.7+66-14.5}\text{s}^{-1} = 10^{41.8}\text{s}^{-1} \; H_{20.5} \, , \qquad (1.12)$$

integrating to an ion number $N = 10^{59.3}H_{20.5}$ within 10^{10}yr, or more than $10^2\text{M}_\odot$ in mass.

This escaping cosmic-ray plasma suffices to *fill* the present *Halo* of the Milky Way. In order to see this, you could calculate the pressure which it exerts when distributed uniformly throughout the Halo. Even faster is the consideration that 10^{10-7} releases (within 10^{10}yr) from the box of height H would fill a truncated cylinder volume of height $10^3 H = 10^2\text{kpc}$ at unreduced pressure, a pessimistic estimate.

Actually, a lot of neutral hydrogen is seen in the Halo, via its 21-cm radiation. Much of it is arranged as a band of falling *high-velocity clouds*, i.e. of cold clouds ($T \approx 10^2\text{K}$) which rain down into the Milky Way, at free-fall speeds of $\lesssim 10^{2.3}\text{km/s}$ which are distinctly smaller than if they came from outside of it (at escape speed, some $10^{2.7}\text{km/s}$). Apparently, these clouds have formed via condensation in the Halo, after evaporation from the Disk, similar to dew on grass stalks. (The rising component is not detected.) Many of them are associated with tiny *intermediate-velocity clouds* which contain molecules; they could have resulted from the high-velocity clouds by having been blown at smoothly, with a light gas – the Galactic twin jet? – as their braking requires a large, smooth momentum transfer, at an inclined angle w.r.t. the Disk. This fountain-like phenomenon involves a mass rate of some $\text{M}_\odot/\text{yr}$, [Kundt, 1997].

Besides these (well-sampled) high-velocity clouds, the spectra also show a diffuse, spherically distributed component of high-velocity HI, of mass $10^{6.5\pm1}\text{M}_\odot$, mass rate $10^{-2\pm1}\text{M}_\odot/\text{yr}$, perhaps a true *fountain* phenomenon involving small filaments which have been shot out of the Disk by supernova explosions, and which subsequently fall back into it. Such filaments also make their appearance through the phenomenon of *refractive scintillations*, during routine surveys of distant point sources whose radiation can be systematically
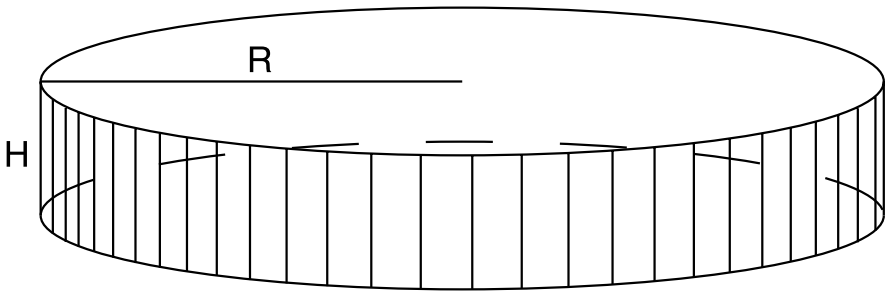

Fig. 1.5. Sketch of the simplified Galactic geometry to estimate the cosmic-ray storage volume of the Galactic disk, assumed box shaped

modulated (mainly reduced) during several weeks, most likely by a filament crossing the line-of-sight.

At this point, observers tell us the Solar System is sitting near the center of a *local hot bubble* (LHB), not exactly spherical in shape, of radius between 0.1 kpc and 0.2 kpc, which is essentially free of neutral hydrogen. Do we have to dismiss the Copernican principle? Should we not re-interpret the LHB as part of the multi-component Disk structure, with space filled by cosmic rays, both leptonic and hadronic, into which cloudlets of warm and cold hydrogen are embedded – like cirrus clouds in the troposphere, or (remotely) like tree stems seen from inside a wood – with 0.1 kpc as the typical distance between immersions? Galactic disks appear to be multi-structured, with cold condensates immersed in a hot matrix.

The Halo also contains stars, usually old ones ($\lesssim 10^{10.2}$yr), of *population II* – to be distinguished from the younger *population I* in the Disk which is more *metal-rich* – often concentrated in so-called *globular clusters*, i.e. spherical star clusters of mass $10^5 M_\odot$ to $10^6 M_\odot$. Their low spin suggests that they are the cores of formerly much more massive condensations ($\gtrsim 10^2$-fold). Their orbits do not lie in the plane of the Disk; they are highly eccentric ellipses, with the center of the Milky Way as their (near) focal point. Isolated Halo stars have similar orbits to the globular clusters, hence move faster than population I stars, and are known as 'Schnelläufer'; they may have been ejected during the formation of globular clusters. Population II is thought to have formed earlier than population I, from a more primordial gas, whence their low metallicities (of $< 0.1\%$, compared to $\gtrsim 2\%$ by mass); whereby in the astronomical nomenclature, all chemical elements beyond helium (of ordinal number > 2) are called *metals*. Actually, many galaxies (including ours) appear to possess two or more subpopulations of globular clusters, distinct by their kinematics, and (nuclear) chemistry [M.J.West et al, 2004: Nature *427*, 31].

The globular clusters are puzzling in various ways; there are indications that they are the debris of dwarf galaxies accreted by the young Milky Way. For instance: why do very few globulars contain large numbers of *ms pulsars* (23 from $10^{2.3}$ globulars contain $\lesssim 70$ ms pulsars, $\gtrsim 50\%$ of all known, among them: 47 Tuc, M 15, M 5, M 13, Terzan 5, NGC 6624, ordered w.r.t. a falling number of pulsars) which pulsars should have turned off long ago, according to their age distribution in the Disk, and which should have been ejected at birth in the first place, due to a recoil which is thought to exceed escape velocity from the cluster core ($\lesssim (30 \div 60)$ km/s) [Kundt, 1998a]? The naively estimated excess ratio of neutron stars in a few globular clusters exceeds 10^6. (A tentative answer to this puzzle will be given in Sect. 9.1). Or: why are there no planets around the stars of globular clusters?

Returning to stellar populations, there is a demand for yet another *population III*, viz. a massive, short-lived first population of stars which has provided (i.e. burnt and ejected) the metals necessary for populations II and (partially) I. Could they be identical with the vigorously burning, massive centers of *active* galaxies known as *QSO*s (= quasistellar objects), or *AGN* (= ac-

tive galactic nuclei) ? The latter are known to eject strongly metal-enriched material, $\gtrsim 10^2$-times solar, the ashes of nuclear burning; they are commonly attributed to supermassive Black Holes (BHs) as the *central engines*, but are perhaps *burning disks* (BDs), the nuclear-burning cores of the galactic disks [Kundt, 2002]. Chapters 6 (on disks), and 11 (on bipolar flows) will deal with them.

What temperature can we assign to the Galactic Halo? In astrophysics, temperatures are almost exclusively determined from the spectra, by comparison with Planckian (or blackbody) radiation, see Fig. 1.6. A Planckian need not imply a uniform temperature in the emission region. But even if the particles of a luminous medium have velocity distributions described by Maxwellians, i.e. have a uniform *kinetic temperature*, a true thermal equilibrium is rare: often the corresponding (large numbers of) photons are missing. More carefully, therefore, one should speak of *kinetic temperatures*. The true temperature of the Universe reads presently 2.725 K, corresponding to a microwave blackbody radiation which peaks at a wavelength of 1 mm, with $10^{2.6}$ photons per cm^3; it is omni-present, and contains almost the whole entropy of the cosmic substratum. Nevertheless, the Halo contains (sub-) populations of
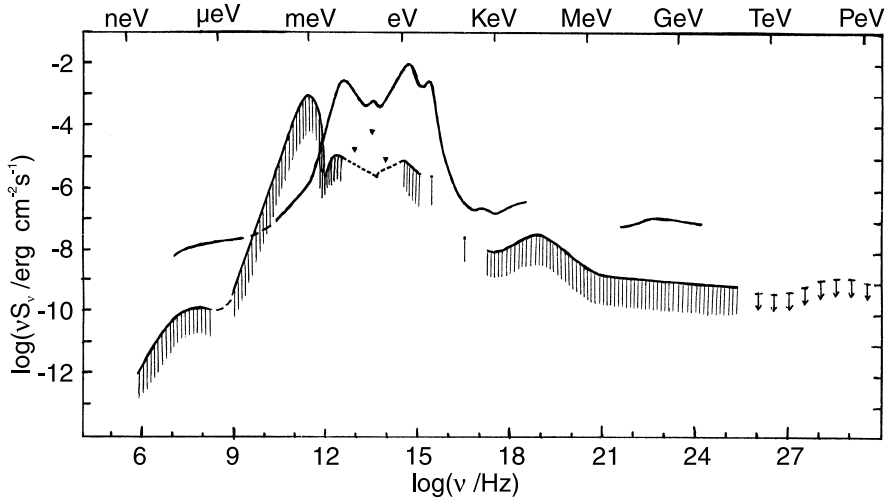

Fig. 1.6. Coarse spectra of both the Cosmic Background (per steradian; vertical hatching) and of our Galaxy, $\log(\nu S_\nu)$ vs $\log \nu$ or $\log E$, with large uncertainties wherever the foreground is bright and/or opaque. Note the energetic peak of the background near 1 mm wavelength, corresponding to 2.725 K, and the two Galactic peaks at visible and far-IR frequencies. Spectral luminosity L_ν and spectral flux S_ν of our Galaxy are related through $L_\nu = 10^{46} \text{cm}^2 \, S_\nu$. [See Nature 390, 257 (1997); Henry: Ap. J. 516, L49 (1999); Franceschini et al: A & A 378, 1 (2001)]

a multitude of (kinetic) temperatures, from molecular-cloud (10 K) through atomic (10^2K) and ionic ($\gtrsim 10^4$K), all the way up to extremely relativistic.

Problems

1. How long does pressure equilibration take through a distance d in a gas of temperature T? Calculate the *sound-crossing time* $t(d,T)$ for a) the solar wind ($d = 10^{13}$cm, $T = 10^{5.7}$K), b) the ISM ($d = 10^2$pc, $T = 10^4$K or 10^{13}K), and c) the IGM ($d = $ Mpc, $T = 10^7$K).

2. *Oscillation time* through the Galactic *Disk*: Calculate the free-fall time $P/4$ of a mass point from a height $\mid z \mid_{\max}$ above a plane mass layer of thickness $2H$, homogeneous mass density $\rho = 10^{-23}$g cm^{-3}, with $H = 10^{2.5}$pc, for the cases a) $\mid z \mid_{\max} \leq H$, b) $\mid z \mid_{\max} \gg H$; call $\sigma := 2H\rho$. Help: you have to solve the oscillator equation $\ddot{z} = -g_\perp(z)$ for the gravity acceleration $g_\perp$ obeying Laplace's equation $g'_\perp = 4\pi G\rho$.

3. For what particle energy $E = \gamma m_0 c^2$ (in eV) does *Larmor*'s *gyration radius* $R_\perp = \gamma\beta_\perp m_0 c^2/eB$ of a proton in the Galactic magnetic field $B = 10^{-5.3}$G become comparable with the scale height $H = 10^{2.5}$pc of the Galactic Disk? Assume $\beta_\perp = \beta$; $\boldsymbol{\beta}_\perp := \boldsymbol{\beta} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{\beta})/B^2$, $\gamma := m/m_0$.

4. Are *galactic disks transparent* in the visible? A layer of optical depth $\tau = N\sigma$ transmits only $e^{-\tau}$ of all photons, where $\sigma = 10^{-24\pm1}$cm^2 is the mean absorption plus scattering cross section per particle (for the cloud-free, and nebula-free ISM at 10^4K), $N :=$ column density. Calculate $e^{-\tau}$ for a) lines-of-sight perpendicular to the Disk, for a mean particle density $n(z) = n(0)e^{-|z|/H}$, $n(0) = 10^{-1.5}$cm^{-3}, $H = 10^{2.5}$pc, b) roughly parallel to the Disk, though not through clouds, with $H = 10$ kpc, and c) through a cloud of thickness 10 pc, mean density $n = 10^5$cm^{-3}, with $\sigma = 10^{-23.5}$cm^2.

5. How does the gravitational lifetime Δt_g of a star (of mass M, contracting under its self-attraction) compare with its *hydrogen-burning lifetime* Δt_h (spent on the main-sequence)? For simplicity, assume (i) a constant luminosity $L = L_\odot(M/M_\odot)^{3.5}$, (ii) an available gravitational energy $\int pdv \approx GM^2/2R$, (iii) $R \sim M^{1/2}$, and (iv) a liberable nuclear energy of $10^{-3}Mc^2$, and express the result through the star's Schwarzschild length $\hat{M} := GM/c^2$.

6. Masses and densities of the bound *celestial bodies*: asteroids, planets, stars, white dwarfs, neutron stars, and black holes (if such exist) can be estimated from fundamental physics by equating the mean pressures which support and confine them. Approximate the repulsive *Fermi-Dirac pressures* and attractive {*electromagnetic/gravitational*} *pressures* by

$$p_F = \left\{\begin{array}{l} (3\pi/5)(\pi/3)^{1/3}\hbar^2 n^{5/3}/m \text{ , NR} \\ (3/4)(\pi/3)^{2/3}\hbar\, c\, n^{4/3} \quad \text{, ER} \end{array}\right\}, \quad p \approx \left\{\begin{array}{l} e^2 n^{4/3} \qquad\qquad \text{, elm.} \\ G(M^2 m_p^4 n^4)^{1/3} \text{ , grav.} \end{array}\right\}$$

$$(1.13)$$

with $m_p :=$ proton mass, NR := non-relativistic. a) The typical laboratory density n_{elm} – equal at this approximation to the asteroidal density – follows from $p^e_{F,NR} = p_{elm}$, the typical planetary density n_{grav} from $p^e_{F,NR} = p_{grav}$, and the maximal density of {white dwarfs/neutron stars} from $p_{F,NR} = p_{F,ER}$ for {electrons/protons}. b) Chandrasekhar's maximal mass of cold stars follows from $p_{F,ER} = p_{grav}$, Fowler's maximal planetary mass from $n_{grav} = n_{elm}$, and the minimal black-hole mass from $M_{BH} \gtrsim nm_pR^3$ with $R \approx GM_{BH}/c^2$ (Laplace, Landau–Oppenheimer, Lynden–Bell). The results are suitably expressed by the nucleon mass m_p, number density n, fine-structure constants $\alpha := e^2/\hbar c$ and $\alpha_G := GM^2/\hbar c$, and by the Compton wavelengths $\lambda_j := h/m_jc$. c) An asteroid turns into a (spherical) planet when it yields to shear forces; the thus determined minimal planetary mass is smaller than Fowler's maximal one by over a factor of m_p/m_e.

1.4 World Substratum

What is our world made of? First in mass, and second in number – after the photons of the 3-K background radiation – ranges *hydrogen*, see Fig. 1.7. Modern cosmology often allows for non-baryonic, *exotic* matter as a possible abundant constituent, but so far, there is no direct evidence for this at all. Consequently, the world's substratum is far from its stable final state (at subnuclear pressure): *iron*. We live far from thermodynamic equilibrium. The chemical composition of Earth is far from typical.

We determine the composition of matter in the Universe from the spectra of stars, emission nebulae, clouds, as well as dispersed absorbers. *Helium*, the second most frequent element, is some ten times rarer in number than H, though only some 2.5 times rarer in mass. There was no chemical equilibrium in the dense initial state of the cosmos, soon after the *big bang*. In the model of the hot (i.e. thermalized) big bang – better called *big flash* – helium is formed from hydrogen during the first three minutes, in the rapidly expanding cosmic soup; it is formed much later in the model of the cold (non-thermalized) big bang, by population III stars. In the process of its formation, its huge binding energy of 7 MeV per proton is liberated; those sites should therefore belong to the brightest *cosmic sources*, brighter than present-day galaxies. Candidate sources are the 3-K background radiation, whose energy density must have been a larger – or even dominant – fraction of the cosmic substratum when it formed, because its energy density drops faster during adiabatic expansion than that of rest-mass-non-zero constituents; but so are the QSOs (quasi stellar objects) and quasars (quasi stellar radiosources), the nuclei of (radio-quiet and radio-loud) active galaxies.

The abundances of the heavy elements, beyond helium, roughly decrease exponentially with their ordinal number – with the exceptions of lithium, beryllium, and boron which are extremely under-abundant, by factors of order 10^{-7}. Moreover, there is an even-odd asymmetry w.r.t. ordinal numbers. All
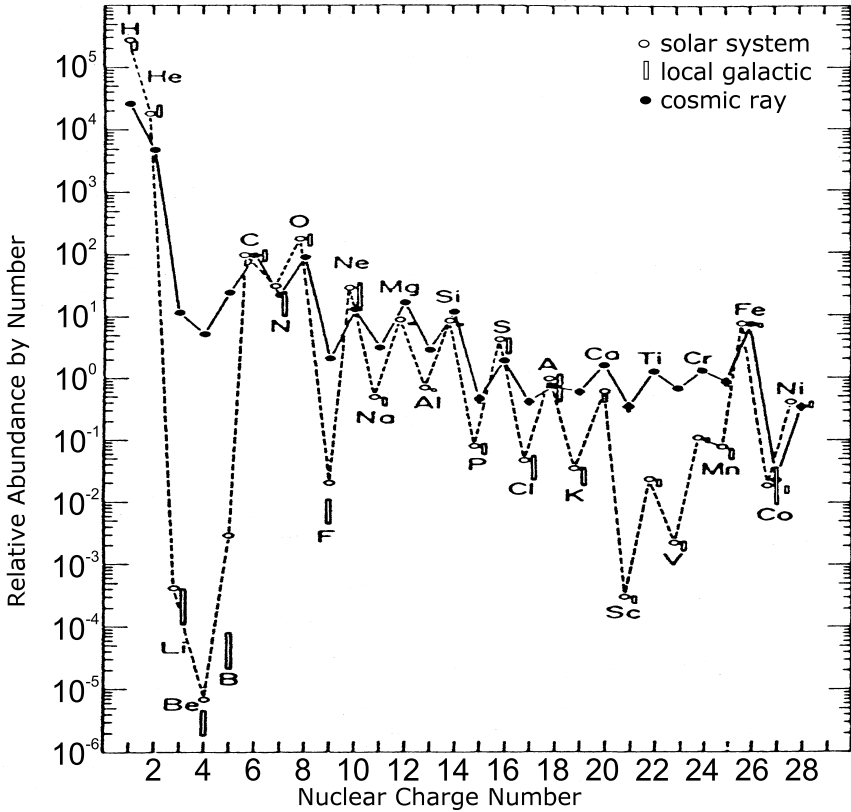
Fig. 1.7. Relative Abundances by number of the chemical elements, in the solar system, in its local Galactic environment, and in the cosmic rays. Note that their average drop with nuclear charge number is exponential, that deep gaps in their distribution are filled up in the cosmic rays (by collisional spallations), and that H and He are depleted in the cosmic rays

these abundances should be understood as the result of nuclear burning inside stars which subsequently eject (part of) the ashes of their burning in their winds, or explosively in novae, or in supernovae. This balance must not forget the QSOs, as the spectra of their BLRs (broad-line-regions) are spectra of nuclear ashes, exceeding solar metallicities (up to iron) by factors of $\gtrsim 10^2$. The BLRs are the ejection regions surrounding QSOs whose velocities reach large fractions (10^{-1}) of the speed of light.

In more detail, one distinguishes between *Solar-System abundances, local-Galactic abundances,* and the abundances of the *cosmic rays;* whereby Solar-System abundances can again be sorted into *solar surface* (or *chromospheric,* found from spectral analysis) and *solar wind* (collected by spacecraft): The

more easily ionizable elements, with $\Phi_{ion} < 8$ eV, are some three-fold enhanced in the wind. Most prominent among the different distributions is the smoothness of the element distribution in the cosmic rays: Relative to carbon, hydrogen and helium are strongly depopulated (when compared with local Galactic), and all under-abundances (Li, Be, B, F, Sc,...) are filled up by the spallation products of neighbouring nuclei of higher ordinal number. Consequently, the cosmic rays have not simply been formed by random accelerations of the interstellar medium (ISM); selection processes must have held back the light elements (H, He), and those not easily ionized.

At this point, I am impressed by how friendly-for-life our planet *Earth* has been equipped (chemically). It is apparently not unimportant that the elements C, O, and Fe form relative maxima of the cosmic production.

1.5 Distance Ladder

Our knowledge about structures in the Universe depends crucially on our knowledge of their *distances*, because sizes, transverse velocities, densities scale with powers of distance and are often at the root of a correct interpretation. For instance, our $\gtrsim 1999$ estimates of the distances of the sources of the daily γ-ray bursts differ by factors of $\gtrsim 10^8$, from $\lesssim 0.1$ kpc to $\gtrsim 10$ Gpc, with corresponding differences in the involved energies by factors of 10^{16} (see Chap. 10). It is therefore important to use as many independent methods as possible for determining reliable distances.

At present, we know of *six* principally different *methods* to determine distances which together allow us to climb the ladder all the way up to the edge of the observable Universe. They are:

1. *Parallax method*: Stars which are near enough to project measurably onto different sky positions during a year, due to the Earth's revolution around the Sun, perform small yearly ellipses on the sky. Their distances d can be calculated from

$$d = v_{\oplus}/\mu\,, \qquad (1.14)$$

where $v_{\oplus}$ is the velocity of the Earth around the Sun, and μ is the object's (2-d) angular velocity on the celestial sphere, or the observing telescope's angular velocity, called parallactic motion, see Fig. 1.8a. An overhead object has the distance of 1 pc when its yearly circle in the sky has a parallactic radius of one arc second: pc = AU/$1''$ = $10^{13.2+5.3}$cm = $10^{18.5}$cm. Clearly, this method can only be applied to cosmic nearest-neighbours, (namely at distances < 10 kpc for angular resolution < 10^{-4}arcsec).

2. *Headlight method*: Whenever one deals with objects of known intrinsic luminosity L, one can use the headlight method familiar from judging the distance of approaching cars at night, on a straight road:

$$d = \sqrt{L/4\pi S} \,, \tag{1.15}$$

where S is the energy flux (= energy per area and time) arriving at Earth. This method has been applied to (i) *main-sequence stars*, burning H to He like our Sun, whose luminosity $L(T)$ is a known function of their observed temperature. It has been likewise applied to (ii) *Cepheïd* and *RR Lyrae* stars, viz. oscillating stars whose luminosity $L(P)$ has been found to be a unique function of their brightness-oscillation period P, (iii) the (ten) brightest stars of a galaxy, (iv) the brightest planetary (emission) nebulae, and (v) the brightest star clusters of a galaxy, all of which have similar luminosities for similar types of galaxies. Even (vi) the brightest galaxies in large clusters of galaxies have been used as *standard candles* for their distance determination. The best standard candles for cosmic distances may be (vii) *supernovae of type Ia* near maximum light, because of their huge luminosities and remarkable similarity, though even this small subclass of SNe does show non-uniformities in their spectra and lightcurves at various frequencies which signal individualities.

3. *Star-Stream Parallaxes*: Stars tend to be born in groups, or clusters, with more or less vanishing peculiar velocities (w.r.t. their center of mass). Due to the laws of perspective geometry, these stars appear to move in the sky along straight lines (great circles) all of which intersect in a distant point of convergence, at angular distance θ, see Fig. 1.8b. Their transverse velocity $v_\perp$, and line-of-sight velocity $v_\parallel$ obey $v_\perp = v_\parallel tg\theta$, so that their distance $d = v_\perp/\mu$ is given by

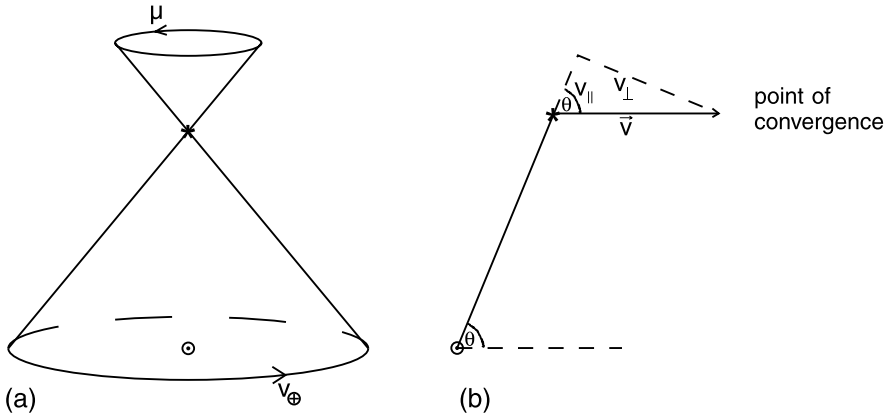$$d = v_\parallel tg\theta/\mu \tag{1.16}$$

Fig. 1.8. (Apparent) Parallactic Motion of nearby objects in the sky: (**a**) stars, due to the yearly motion of Earth around the Sun, and (**b**) (kinetically cool, young) star clusters with a significant (uniform) bulk velocity relative to the solar system

as soon as $v_\parallel$ is known. But $v_\parallel$ can be measured via the Doppler effect whose general formula is provided by the Special Theory of Relativity as

$$\nu'/\nu = 1/\delta := \gamma(1 - \beta\cos\vartheta) \stackrel{\vartheta=0}{=} \sqrt{(1-\beta)/(1+\beta)} \approx 1 - \beta \qquad (1.17)$$

in which ν, ν' are the frequencies measured by the source and observer, respectively, whereby the source recedes at velocity $c\beta$, at an angle ϑ w.r.t. the line-of-sight, and where $\gamma := 1/\sqrt{1-\beta^2} =$ Lorentz factor, $\delta :=$ Doppler factor. For small $\beta_\parallel := \beta\cos\vartheta$, this Doppler formula simplifies to

$$-\Delta\nu/\nu \approx \Delta\lambda/\lambda \approx \beta_\parallel \qquad (1.18)$$

with $\Delta\nu := \nu' - \nu$. The Doppler effect allows to determine $v_\parallel$ whenever the source emits, or absorbs at least one identified spectral line.

4. *Baade–Wesseling method*: When a luminous, expanding or revolving source has spherical or circular symmetry, a measurement of its maximal approach speed $v_\parallel$ implies a knowledge of its maximal transverse speed $v_\perp$, which is independently observed as a parallactic speed μ. With this, (1.14) becomes applicable; no nearer rungs of the distance ladder are required. This method has been applied to several resolved supernovae (for spherical symmetry), and recently also to masers on an inner Kepler orbit around the rotation center of the galaxy NGC 4258 (for circular symmetry).

5. *Cosmic expansion*: As noticed by Edwin Hubble already in 1929, distant cosmic objects recede from our Galaxy at speeds which grow, to first order, linearly with their distance. This general recession, or *Hubble flow* of galaxies is a consequence of the cosmic expansion, and is thought to be independent of the observer's position in space: at fixed cosmic time, all distances d grow roughly at the same rate $H(t) = \dot{d}/d$. The present value H_0 of the Hubble parameter H, $H_0 := H(t_0) = (70 \pm 20)$km/sMpc $= 10^{-17.65\pm0.15}\text{s}^{-1}$, is of order 1/age(Universe). Homo Sapiens owes his existence to this long time-scale, because biological evolution alone takes some $10^{0.6}$Gyr. Using (1.18), the distance d of a distant enough galaxy is approximately given by

$$d \approx cz/H_0 \quad \text{with} \quad z := \Delta\lambda/\lambda \approx \beta_\parallel \ . \qquad (1.19)$$

Clearly, this method has an intrinsic uncertainty controlled by peculiar velocities $\delta\beta_\parallel$, which can be as large as 1%.

6. *Gravitational lenses*: Every local mass concentration can serve as a gravitational lens, by bending ambient light rays towards it, i.e. by making light signals detour – an effect which transcends Newton's and Maxwell's theory. In practice, 1 out of 500 distant sources is significantly enhanced by a foreground lens, by an arbitrary factor which tends to be several. If a lensed object is rapidly time-variable, its two or more images will vary with specific delays, independent of frequency, which can be read off their lightcurves. In this way, angular separations can be converted to linear separations, and their distances determined.

Problems

1. How sensitive must an optical spectrometer be in order to resolve line-of-sight velocities $c\beta\cos\vartheta$ of size a) 10 km/s, b) 10^2km/s? Express the *spectral resolution* through $\Delta\lambda$.

2. At what distance d does *Hubble's expansion velocity* $\dot{d} = H_0 d$ reach the magnitude of {stellar/galactic} peculiar velocities Δv (of $\{10^2/10^3\}$km/s)?

1.6 Galaxies, Clusters of Galaxies, IGM, and Sponge Structure

In the sky, we do not only see our Solar System, in the foreground, and the Milky Way, in the middle ground, but also uncounted numbers of *galaxies* which arrange themselves more or less in clusters, or superclusters, or even in a large-scale ($\lesssim 10^2$Mpc) *sponge structure*, with underpopulated *voids* surrounded by sheets. The background of galaxies reaches to the edge of visibility, presently out to redshifts $z := \Delta\lambda/\lambda \lesssim 7$, (even $\lesssim 10$, detected in the ultra-deep field), corresponding to distances from where the wavelengths of emitted radiation arrive $(1 + z) = 8$-fold redshifted. At the time of such emission, the world was some $(1 + z)^{3/2} = 23$-times younger than it is now; see Plates 14 and 15.

A rule of thumb says that our Galaxy harbours 10^{11} stars, and the cosmos harbours 10^{11} galaxies. *Galaxy masses* reach down to $10^7 M_\odot$ – of the smallest detected dwarf galaxies – and up to $10^{14} M_\odot$, of the central cD-galaxies of large clusters which have significantly grown in mass – so we think – by galactic cannibalism. The *galaxy-luminosity function* is quite similar to the stellar one, Fig. 1.2; so far, the number of galaxies increases (slowly) with decreasing luminosity [MNRAS 2000: *312*, 557]. As a rule, we only see the (exponentially brighter) central part of a galaxy – comparable to the tip of an iceberg – and are often taken by surprise when at different wavelengths (21cm, radio, X-rays), or in deeper maps, a galaxy reveals its $\lesssim 10$ times larger halo, and/or galactic associations.

Galaxies can have very different *morphologies* : The *Hubble sequence* arranges them linearly, as a tuning fork, with clean ellipsoids at the grip end, disks with spiral-arm structure with or without a *bar* in the two forked arms, and irregular galaxies at the other end(s); more careful classifications (by de Vaucouleurs, W.W. Morgan, S. van den Bergh) use 3-d, or multiply branched arrays. Spiral galaxies without a bar look like tropical storms (cyclones, hurricanes, typhoons) seen from outer space, see Plate 13.

Common to all galaxies is their composition, of gas and stars, the latter usually as constituents of a – more or less extended – disk. The gas (or rather plasma) in the disk rotates differentially, according to Kepler's (generalized) law, exerts magnetically mediated friction, thereby loses angular momentum

to adjacent material further out, and spirals in towards the center, at average rates of $\lesssim M_{\odot}/\text{yr}$. Consequently, galactic disks are not stationary – comparable to the (changing) cells of our body – but are replenished from outside, on the time-scale of cosmic evolution, often at different orientations. In galactic nuclei, matter therefore piles up repeatedly, resulting in (i) dense *molecular tori*, (ii) violent star formation (*starbursts*), (iii) coronal emission (*LINER*, = low ionisation nuclear emission region), and (iv) an *active galactic nucleus* (*AGN*), all four of which add to the morphological appearance of their host galaxy, because of their non-ignorable brightness.

In addition, an active galactic nucleus can lead to the formation of two antipodal (*supersonic) jets*, in roughly 10% of all cases, more frequently so for high-luminosity sources. These jets ram vacuum channels into the circumnuclear and circumgalactic medium (CGM), of lengths up to several Mpc, of knotty appearance (with *hotspots*), and thereby blow *lobes*, or *cocoons* that belong to the largest, and strongest radio emitters in the Universe. Their cores tend to be observed as (compact) BLRs surrounded by (galaxy-scale) narrow-line regions (NLRs). Our highly controversial understanding of their functioning will be the subject of Chap. 11.

Galaxies often form groups, and associate in clusters, and in superclusters which reach sizes of 10 Mpc. The *superclusters* contain a lot of plasma which radiates at X-ray temperatures; one talks of *cooling flows* because the radiating plasma appears to fall into the supercluster from outside, thereby heating up in the outer zones (10^8K), and subsequently cooling in the denser core regions (10^7K). The inferred plasma densities n lie between 10^{-7}cm^{-3} and 10^{-3}cm^{-3}. The peculiar velocities in large galaxy clusters can be quite high ($\lesssim 10^{3.3}\text{km/s}$), and an application of the virial theorem to them – assuming they form bound systems – leads to masses which tend to distinctly exceed the sum of the visible masses of all components, by an order of magnitude; we deal with missing mass, with *dark matter* ! Such mass estimates tend to be corroborated by estimates of their X-ray emitting cooling-flow gas, or by estimates based on their action as gravitational lenses, i.e. by their ability to focus the light of more distant sources. Is this dark matter hot (*HDM*), consisting of yet to be discovered (relativistic) elementary particles, or is it cold (*CDM*), consisting, perhaps, of clumped baryonic matter? The dark matter appears to concentrate in the cluster cores where the virial estimate yields an underestimate.

What medium fills the cosmic volume, the space between the galaxies? The approximate cigar shapes of the (lobes of the) extragalactic radio sources indicate that the stalled jet material meets with resistence as it expands subsonically into a medium of density $n \gtrsim 10^{-7}\text{cm}^{-3}$, temperature $T(IGM) \gtrsim 10^7$K, the latter from X-ray maps of large galaxy clusters. A lack of Lyα-edge absorption in the continuum spectra of background QSOs implies a much lower average neutral-hydrogen density, $n_H \lesssim 10^{-11.8}(1 + z)^{3/2}\text{cm}^{-3}$, hence again a high temperature of the volume-filling intergalactic plasma, $T \gtrsim 10^6$K, in order to have a high enough degree of ionization. I.e. the pressure of the

intergalactic medium (IGM) is exerted by a rather thin and hot plasma, probably predominantly hydrogen. Note that a clumpy, cold component of the IGM would escape all our observations, for a wide range of grain sizes, hence cannot be excluded.

QSO spectra do, however, show hundreds of discrete Lyα absorbers, of column densities N_H power-law distributed according to $dN/d\ln N_H \sim N_H^{-0.5}$, between $10^{12} \lesssim N_H/\mathrm{cm}^{-2} \lesssim 10^{20.5}$, of inferred temperature $\approx 10^{4.3}$K and velocity dispersion $\gtrsim 5$ km/s – the *Lyα forest* – whose origin is ill understood. The extents of individual absorbers range from $N_H/n \gtrsim$ AU up to Mpc. Their metallicities Z are $\lesssim 10^{-3} Z_\odot$. But there are corresponding *metal-line absorbers*, occurring $\lesssim 30$ times less frequently, often hydrogen depleted, with a similar distribution. Both absorber systems are spatially distributed like the halos of glaxies, some tenfold expanded, with a similar joint chemical composition. They cannot be (staticly confined) cloudlets because they would evaporate in subcosmic times. Marita Krause and I have interpreted them as filamentary supersonic ejecta from *active galactic nuclei*, diffusively segregated into metallic cores and hydrogen envelopes [1985: Astron. Astrophys. *142*, 150-156].

Out to what spatial scales does one detect inhomogeneities, i.e. structure in the Universe? Galaxy catalogues – including redshift measurements, for an estimate of their distances – have revealed a cosmic *sponge structure*, on the scale of 10^2Mpc: The galaxies cluster with the geometry of a sponge, for redshifts $z \lesssim 6$, forming 2-d sheets which intersect in filamentary (1-d) edges, the latter perhaps meeting in 0-d vertices. In between the sheets are voids whose sizes would require speeds of order 10^2Mpc/10 Gyr $= 0.03c$ if they were to be evacuated in the recent past, unrealistically large. This density structure must have been established in the early Universe.

Is there structure on yet larger scales (than 10^2Mpc)? Among the split opinions discussed in the literature, the conservative one argues for asymptotic homogeneity [Wu et al, 1999] – so that the homogeneous-isotropic cosmological models of General Relativity become applicable – whereas a minority opinion argues in favour of a hierarchical, or fractal structure all the way up.

1.7 Cosmology

Our best theory of gravity is Einstein's theory of *General Relativity*. It generalizes, at the same time, Newton's theory to large velocities, and the Special Theory of Relativity to high mass concentrations; and it allows a straightforward embedding of Maxwell's theory of electromagnetism. Should it be quantized? I see no obligation, already because of an absence of predictions and tests. Promising attempts have been made to even incorporate the electromagnetic, *weak*, and *strong* interactions between elementary particles into a unified, deterministic, parameter-free, $\geq$ eight-dimensional (Ricci-flat) generalization of it called *metron theory* [Hasselmann, 1998].

Einstein's field equations read:

$$G_{ab} = \kappa T_{ab} - \Lambda g_{ab} \ , \tag{1.20}$$

with $\kappa := 8\pi G/c^4$ being the coupling constant between the 4-momentum properties of matter, described by the phenomenological stress-energy-momentum tensor T_{ab}, and Einstein's curvature tensor $G_{ab} := R_{ab} - (R/2)g_{ab}$, the latter composed of second space/time derivatives of the (dimensionless, 4-d) metric tensor g_{ab}, of signature $\{-,+,+,+\}$; $R_{ab} :=$ Ricci tensor, $\Lambda := $ *cosmological constant*, an inverse area which acts like a repulsion if positive and may, or may not vanish. Modern 'concordance' calls Λ 'dark energy', even though a positive Λ corresponds to a negative energy density (in T_{ab}), but positive pressure, hence is not (proportional to) an energy.

According to our knowledge, the Universe should be describable by a solution of (1.20) for all distances and times, including its beginning. The *conservation laws* of baryon number B, lepton number L, and charge Q, assumed to be valid throughout, allow us to apply them even to its much denser initial stage which may start with a singular beginning, the so-called *big bang* (after Fred Hoyle), or *big flash*. For a non-negative non-gravitational energy density ρc^2 (with Λ incorporated into T_{ab}), such a singular beginning is unavoidable [see Kundt, 1972]. But a repulsive Λ, or a slight violation of the conservation laws (*continuous creation*) can avoid a singular beginning, in favour of an infinite sequence of bounded oscillations [Hoyle et al., 2000]. Unavoidably, all our conclusions turn uncertain with increasing distance from here and now.

How certain can we be that the *laws of physics*, learned here and now in terrestrial laboratories, still apply literally at large spatial and temporal distances, in particular near the big bang? Among the most plausible changes would be variabilities of the *dimensionless fundamental constants,* such as $\alpha := e^2/\hbar c$ and $\alpha_G := Gm_p^2/\hbar c$, or ratios of masses (like m_p/m_e), or charges of the elementary particles. (Note that fundamental units with a dimension, like c or $\hbar$, are constant by definition, cf. Sect. 1.1). Such changes would, e.g., show up through variable frequency ratios of spectral lines, or variable ratios of nuclear reaction times. So far, reassuringly, none of the reports of this kind have stood the test of time, with, e.g., $\mid \dot{\alpha}/\alpha \mid \leq 1/10^{16.2}$yr, [Cowie & Songaila, Nature *428*, 132 (2004)].

So we are confident to eventually come within grips of our cosmic past. The mean mass density in the Universe should not be distinctly smaller than the *critical density*

$$\rho_{crit} = H^2/8\pi G = 10^{-29.4} \mathrm{g\,cm}^{-3} \ H_{-17.6}{}^2 \tag{1.21}$$

which is obtained from the time-time component of (1.20) for a homogeneous-isotropic model with $\Lambda = 0$ (because of $G_{00} = H^2/c^2$, H as in (1.19)). This critical mass density corresponds to one hydrogen atom per m^3. We owe our existence to its smallness, as it has given Earth enough time for life to evolve.

The present value of the *density parameter* $\Omega := \rho/\rho_{crit}$ should not distinctly exceed unity (for the Universe to be old enough); it may be some

30-times smaller, even with dark matter included. With this, the world is $\gtrsim 10^{10}$yr old, has an observed extent (of the backward light cone) of $\gtrsim 3$ Gpc, and will probably expand for all times, i.e. not recollapse under its own attraction, (the hyperbolic case of expansion).

A basic fact of cosmology is the 2.725 K background radiation, the cosmic carrier of entropy (or modern *ether*), whose 10^{-3} dipole anisotropy at the solar system tells us our state of motion w.r.t. the substratum. Its impressive *blackness* ($\gtrsim 10^{-4}$) and unexpected *isotropy* ($\lesssim 10^{-5}$) on all angular scales – with a peak of fluctuations at $1°$ – are embarrassing for all cosmological theories, already because of fluorescent re-emissions of Lyman-edge absorptions after decoupling (from matter). Has it been smoothed by a presently invisible scatterer, such as carbon or iron *whiskers*, or hydrogen snow before its vaporization?

Why is the night sky not as bright as the day sky? This seeming *paradox*, first highlighted by Heinrich *Olbers*, crops up if we naively assume that space is infinite, and filled uniformly with stars like our Sun: eventually, for large enough distance, the stars should cover the whole sky. In reality, a glance at Fig. 1.6 teaches that our Milky Way shines at us with only some 10^{-2}erg/cm^{2}s, some 10^{-8} of the solar flux $S_\odot = 10^{6.1}$erg/cm^{2}s, and that the rest of the Universe adds some 10^{-5}erg/cm^{2}s $\approx 10^{-11}S_\odot$ to this flux.

These numbers are plausible when one calculates the relative spherical angles covered by the respective stars: The Sun covers a fraction $\pi R_\odot^2/4\pi(\text{AU})^2$ $= 10^{-5.27}$, the Milky Way (with its 10^{11} sun-like stars at separations between a pc and many kpc) covers (only) some 10^{-13} because visible light gets increasingly absorbed by foreground dust beyond distances of a few 10^2pc; and all the other 10^{11}galaxies, at distances $\gtrsim$ Mpc, would cover another fraction of 10^{-13} when integrated out to distances of some 3 Gpc. This last number (of cumulative relative sky coverage) grows roughly linearly with distance for a uniform density of galaxies in Euclidean space. It should even be enlarged by (i) a small proportion of stars outside of galaxies, also extended 'nebulae' illuminated by stars, and by (ii) the fact that at cosmically early times, volume densities were higher. On the other hand, (iii) there is significant absorption of starlight by cold dust between the stars, of order $\gtrsim 0.9$, (iv) star formation has not yet started at redshifts z much larger than 10, i.e. our past is not infinite, and (v) with increasing distance, the starlight gets increasingly redshifted so that arriving visible light stems from the stars' (much dimmer) UV. Taken together, these five corrections reduce the effective relative sky coverage of distant emitters to some 10^{-16}, less than 10^{-10} of looking straight into the Sun (at daytime). Remarkably, the eyes of creatures like man have just this enormous *dynamical range*, $1 : 10^{-10}$, that allows them to see their surroundings at day and at night.

What else can we learn from cosmology? We should like to know when and where hydrogen was burnt to the present-day distribution of the chemical elements, the light ones (D, He, Li, Be, B) and the heavy ones (C and beyond: in the first three minutes, or much later, in stellar processes?); when the

background radiation was formed and decoupled from matter: at redshift $z = 10^{3.13}$, or much later, at $z \gtrsim 10$ (?); how the cosmic *sponge structure* came into existence, including the $Ly\alpha$ forest, and how all the (various) *galaxies* formed : from above in mass (top down), or from below in mass (bottom up), or both at once? Unconventional answers to these problems are given by Hoyle et al. [2000], conventional ones in Peebles [1993]. Was the big bang *hot*, i.e. thermalized, or *cold*, i.e. initially photon-free [Layzer, 1990]? Do all the (generalized) *charges* initially vanish, like net charge Q, baryon number B, lepton number L, cosmological constant Λ [Blanchard, A. et al, A & A *412*, 35 and L37 (2003)], or is Wolf Priester's $\Lambda = 3H_\infty^2/c^2$ indispensible?

How did the *magnetic seed fields* form, which have led to equipartition strengths on galactic and even on cluster scales, and from which the stars, and the planets inherited their initial fields? Squeezed via shearing in galactic and protostellar disks, and subsequently blown out from their cores and stretched via winds, and bipolar flows? Note that ordered magnetic fields of strength $\gtrsim 10$ μG on scales up to $\lesssim 0.5$ Mpc (!) have been inferred from *rotation measures*

$$RM := (e^3/2\pi m_e^2 c^4) \int n_e \boldsymbol{B} \cdot d\boldsymbol{x} = \mathrm{cm}^{-2} \left(\int n_e \boldsymbol{B} \cdot d\boldsymbol{x} \right)_{16.6} , \qquad (1.22)$$

for the central regions of large galaxy clusters [Kronberg, 1994; Scient. American, August 2000, p.13], via a frequency-dependent phase shift $\Delta\Phi = RM\ \lambda^2$ of linear polarization, derivable from (3.17). The rotation measures can exceed $10^4 \mathrm{rad/m^2}$ in the strongest *cooling-flow* clusters, whose infalling plasma glows at X-ray temperatures.

It is not clear how far we have gone yet in answering these cosmological questions reliably.