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IRREVERSIBLE UNIVERSE

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"Make yourself a light!"
(Buddha)

Dynamical Controversy

Exact understanding of Nature started with the Newtonian programme. The success of this programme is due to the fact that the laws of Nature have been formulated as equations of motion. These equation express the trends of change in terms of the present state. If the state of the world is known at a given time, a step by step integration can tell us its future states. This means that the present state of our Universe can be understood if one knows the equations of motion (from local experience) and the initial conditions as well (from elsewhere). Man tried hard to learn these initial conditions from outside of science, but the scientists of the 19th century got worried about this alien input. To be able to explain the material world by itself, a steady state universe was postulated (at least on large scale). In this way physicists hoped to be able to explain the state of the world by looking for the equilibrium solution of the equations of motion.

At the end of the 19th century theoretical investigations led, however, to inherent logical difficulties. Olbers called the attention to the following paradoxon: The light intensity, reaching Earth from a star is inversely proportional to the squared distance of this star. The number of stars in a spherical shell is directly proportional to the squared distance. Therefore each layer contributes to the light intensity by the same amount. The integrated light intensity of a steady infinite Universe would have been infinite. Why is it dark at night?

Clausius formulated an other paradoxon. In a timeless (eternal) universe density, temperature, pressure, concentrations would have levelled up, our world would have had to be in thermal and chemical equilibrium. In this ultimate state of heat death the entropy of the universe (measuring the degree of disorder) would have reached its maximum value. How comes that we experience hot and cold, bright and dark?

Each astronomical body is the source of gravitational lines of force, proportionally to its mass. These gravitational forces do not compensate (as electric forces do) because all masses are of the same sign. If there are gravitational lines of force present, the bodies cannot float, they must accelerate. Only an empty universe could have a steady state. How comes - asked Seeliger - that the sky does not fall onto our heads?

At the turn of the century the greatest minds were ready to modify the empirical equations of motion just to force a steady state solution. A historical shock helped to break through this mental barrier (Petrograd, 1922). Alex Friedman was the first who dared to conclude that the equations of motion didnot have static solutions at all! The world must either contract or expand. The technological revolution on the other hemisphere (the 100 inch telescope on Mount Wilson) has confirmed this conclusion. The universal red shift in the spectra of galaxies has indicated that the galaxies run away from each other. The larger is the distance, the higher is the speed. Hubble's discovery has offered a simple explanation: those galaxies are farer away which run faster. The whole race might start with a Big Bang a finite time ago. This mathematical consequence of the equations of motion and its empirical confirmation has invalidated the logical contradictions mentioned above and it has created new ones.

Thermal Controversy

If our Universe had a very high density in the past, if all the protons, neutrons (quarks) were compressed, how comes that the present world is not dominated by heavier nuclei (like iron) having the deepest binding energy but it abounds in light elements (like hydrogen, oxigen, carbon, nitrogen) which support life? Gamow offered the answer that the early universe was so hot that no composite structure survived. Later on it was cooled down when the expanding gases performed work against their own gravitational attraction.

The equations of motion and the laws of thermodynamics enable us to reconstruct the past history of the Universe. Until the radiation temperature cooled below 10 000 degrees, atoms were completely ionized, interacting immediately with electromagnetic waves. When the temperature dropped below 10 000 degrees, charged particles formed neutral atoms, which became practically invisible (transparent) for radiation. Since that the mean collision time of photons is larger than the age of the Universe, thus the relic radiation depicts the state of the Universe at the end of the Hot Era. (This picture has, however, got red shifted.) The Planck shape of the observed radio spectrum tells us that the Universe was in thermal equilibrium in the past! (No wonder: gravity was able to thermalize the early - hot and dense - world very quickly.) But now our world is certainly not in thermal equilibrium. Heat death is not a menace of future but a fact of the past!?How can a closed system drop out of thermal equilibrium? This is a burning question of science and philosophy since decades. In the next chapters models will be presented to show that the resurrection from heat death is the outcome of an amazing interplay among inherent gravitational instability (leading to fast mechanical expansion) and the realive weakness of some interactions (slowness of thermalization) at certain periods of cosmic history.

The Gas Model

In a cloud chamber the gas mixture of alcohol + air is compressed at the beginning of the operation, it is in equilibrium at room temperature. Then the chamber is expanded quickly, which produces adiabatic cooling. At the decreased temperature the new equilibrium state would be air + liquid alcohol. But formation of droplets needs time, so for a transient time interval there is air

+ overcooled alcohol vapour in the chamber. This is just the short sensitivity period of the cloud chamber: when an ionizing particle passes through, its trajectory will be made visible by the chain of droplets formed around the ions.

Let us consider two equal containers, one filled with argon gas, the other with nitrogen gas; both containing the same number of molecules,therefore having the same pressure of 2 atmospheres. (Figure 1a.) Due to the thermal contact between the two pistons, the two gases are at the same temperature: let us say, at 200°C. In this equilibrium state there are no changes, there is no thermodynamical arrow of time. Let us remove half of the weights! Both gases expand quickly.By raising the pistons,they perform the same work against gravity at the cost of their internal (thermal) energy. The argon cools to 76°C, the nitrogen cools to 121° C. (Figure 1b. The twoatomic nitrogen molecules are elongated, they store energy in molecular rotations as well. To perform the same amount of work, the nitrogen - having larger heat capacity - has to cool less.) Expansion against gravity created temperature difference in this two component system! (One may try to drive a steam engine by it.) But heat conduction begins immediately to level the temperatures. This appearance of the arrow of time is only a transient phenomenon: due to the weak (thermal) coupling between the two pistons, they soon will reach a new thermal equilibrium at a common temperature of 104°C.

In a physical universe no intervention was needed from outside to lift up the lid. Temperature differences might be created automatically in closed system in mechanical disequilibrium. To illustrate this, let us assume that Einstein's expanding world is filled with two different materials: with radiation and with atomic gas.At several thousand degrees the gas is completely ionized and its charged particles scatter radiation. The frequent collisions level the temperatures quickly.But this system cannot be in mechanical equilibrium: it expands (or collapses) under its own gravity. The expanding mixture performs work against gravity, it cools gradually. When the temperature drops below 1000°C, charged particles combine to neutral atoms, which get invisible for radiation. Gas and radiation get decoupled. Due to their different heat capacities, they cool at different rates: While radiation cools from 1000 K to 100 K, gas will cool from 1000 K to 10 K.The slight coupling of electromagnetic waves to (polarizable)atoms is not efficient enough to equalize the temperatures while expansion is running fast.When expansion slows down (when gravitational deceleration has slowed down the runaway), the thermalization may catch up: thermal equilibrium may be reestablished and maintained in the late Universe. (Figure 2 shows the temperature curves for different coupling strengths - dotted lines - and the entropy increase during the era of thermal disequilibrium - solid line - .In the numerical integration the temperature difference was created by the fast expansion in the early period but the heat transfer with fixed a conductivity made it to disappear again. The arrow of time was only transient.In actual cases the atomic density and radiation frequency drop during expansion,therefore the collision times get longer, the conductivity decreases with time. This prolongs the era of irreversibility.)

Such transient disequilibrium eras occur during the history of our actual Universe. In the next chapters we shall recapitulate shortly the Standard Cosmological Model (complemented with the fashionable inflationary scenario of the Grand Unified Theory= GUT), in order to show that in certain periods of time the coupling between two components of cosmic material weakens, the coolision time gets longer than the age of the actual Universe. Different components cool at unequal rates, which leads to transient irreversible processes, entropy gain and possibly structure formation. Just these 'transient structures' give the present characteristic face of the world we live in.

Let Space and Time Be!

Theoretical physicists searching for a consistent mathematical description of fundamental particles have introduced the Grand Unified Theory. One of the conclusions of this theory is that originally all the particles were of equal (zero) mass, all the forces were of equal (infinite) range and equal strength. Differentiation of forces can be attributed to a historical "phase transition": this freezing of the vacuum resulted in an order parameter. As a consequence, different particles (being coupled to the frozen vacuum in different ways) have picked up different potential energies, they have got different rest energies and different masses. Different masses resulted in different ranges of (nuclear, electric, weak) forces.

At the beginning the actual cooling of the Universe was very fast, due to the rapid expansion. But the overall freezing of the vacuum needed a certain time to form ordered domains. The vacuum remained in liquid state for a considerable period in the cold environment. The latent heat of the overcooled vacuum manifested itself as a negative pressure, inflating space and giving its Euclidean structure we observe today. Some moments later freezing started here and there, latent heat was liberated by the vacuum. The heat emitted into the cold environment heated up the materials, increased the entropy and created the particles what we observe today as relic radio noise. (All these might happen at 10^{-38} seconds after the Big Bang.)

Let Protons Be!

Radiation has higher entropy than hydrogen gas of the same energy. Annihilation of protons + electrons into photons would increase disorder in the Universe, it is favored thermodynamically. According to the Grand Unification Theory of matter such transitions may go via the hypothetical X particle:

$$p^{+} + e^{-} \longleftrightarrow X \longleftrightarrow \text{photons} .$$

How comes that there are still photons and atoms and solids around us? (Luckily not too many: one proton per billion photons. One per million would be too much: gravitation would have made the Universe recollapsed long ago! Luckily not too few. One per hundred thousand would have been not enough to build up galaxies and stars in the rapidly expanding diluted world.)

The X particle is expected to be billion times heavier than the proton. In the early hot Universe radiation made X and X produced quarks. Quarks made X and X produced radiation. They co-existed in thermal equilibrium. Then the temperature dropped so fast that some quarks cooled down and they did not have energy enough to produce heavy X. They have become unable to annihilate, they have got trapped in the quark state of low entropy. (Figure 3.) The bound system of three quarks made one proton or one neutron. Protons may decay into radiation very slowly by tunnelling through the X energy barrier, the decay time has been estimated to be loner than 10^{30} years. (Search goes on, to observe proton decay.) This is, why our present world - stuffed mainly by completely disordered radiation - still contains some protons and neutrons as well, as overcooled transient relics inherited from the hot era.

Let Nuclei Be!

The protons(p) and neutrons (n) were in thermal equilibrium:

$$p^{+} + e^{-} \longleftrightarrow n + \text{neutrino}.$$

The number of protons were roughly equal to the number of neutrons.When the temperature dropped below 1 billion degrees (at about the end of the first second), the protons and electrons slowed down, their kinetic energy was not enough to make the slightly heavier neutrons. No new neutrons were produced, but the existing neutrons started decaying:

$$n \rightarrow p^{+} + e^{-} + \text{antineutrino}.$$

After the first second the equilibrium composition of the world would be light + protons + electrons. But the unstable neutrons needed time (about ten minutes) for decaying. They survived for a while in the cool world, in spite of their instability! Free neutrons in a cool environment offered a unique chance for nuclear architecture: some neutrons were captured by protons, making composite nuclei, like heavy hydrogen, helium, lithium. (The thermal motion had got so mild that these structures survived.) But the free neutrons eigher got captured or decayed in the first minutes, the nuclear buildup stopped before establishing thermal equilibrium, before progressing to the most stable iron state. This is the way how the lightest elements were made, how the primordial hydrogen survived.

Heavy hydrogen and lithium could not be produced in stars, where they would burn immediately.They are left over in the outer space by a transient non-equilibrium era. Heavy hydrogen and lithium are energy rich structures, they may turn out to be the fuels of the nuclear fusion reactors of the future.

Let Stars Be!

Later on, during the first million years after Big Bang, the temperature dropped below thousand degrees.The thermal motion got so slow that positive protons (and other positive light nuclei) captured and kept negative electrons. Neutral atoms were born.

They did not interact any longer with the warmer radiation, therefore this gas was cooled fast by the expansion. Statistical fluctuations produced higher density clouds here and there. If the clouds were large enough, their gravitational attraction overcame the thermal motion and kept the cloud together. These stable clouds made the galaxies. There are astronomical indications that galaxies might be formed even earlier by some neutral particles, which did not interact with radiation in the hot era. Due to their rest mass they possessed smaller heat capacity than light, therefore expansion work cooled these heavy neutrals much faster than it cooled radiation. This pre-cooling could enable massive neutrals - massive neutrinos? - to make the very first concentrations. These first clouds became the vombs for clusters of galaxies.)

The galaxy clouds cooled, contracted, even flattened by rotation. In gas regions of higher density smaller gas clouds isolated themselves, they became spherical by the balance of gas pressure and gravitational attraction. Let us call them stars.

Imagine the stars embedded in radiation. At the beginning they might have similar temperatures. The cosmological expansion cooled radiation, but did not affect the internal temperature of the star. (The gas was kept together by stellar gravity, there was no expansion to cool the gas.) The warm star started to give off energy to the cooling environment by thermal radiation, trying to reestablish the isothermal equilibrium. But in vain!

The total kinetic energy of the gas particles in a star is proportional to the average temperature. The total gravitational potential energy of a star is twice as big as the kinetic energy and it is negative. The sum of kinetic and potential energies is negative (the star is a bound system) and it is proportional to the temperature. With other words: the star (and any gravitationally bound system) has a negative heat capacity. While the star radiates energy off to its cool environment, it gets warmer! The Universe tries to reestablish isothermal equilibrium by starshine, but this makes the temperature differences just higher! This is how we have got hot-bright stars on the cold sky.

Let the Periodic Table be Populated!

The present atomic material of the Universe contains today 75% hydrogen - these simplest nuclei - in spite of the fact that deeper binding would be offered by heavier nuclei like iron. Nuclear matter has got trapped in energy rich hydrogen state in the early hot era, when thermal motion overwhelmed nuclear bonds. In the later cool period nuclear buildup was prevented by the mutual electric repulsion among the positive nuclei.

The only exceptional places are the stars. Inside them the gas temperature has been raised by the gravitational work of contraction, offering a new and now lasting chance for nuclear buildup. Its first step would be the fusion of hydrogen nuclei (two protons) to light helium (bound state of the two protons) but such a nucleus does not exist (the nuclear attraction is not strong enough to overcome the electric repulsion and quantum motion). Hydrogen survives even in hot stars. (This is why the hydrogen inside the hot Sun does not explode like a hydrogen bomb.) The only

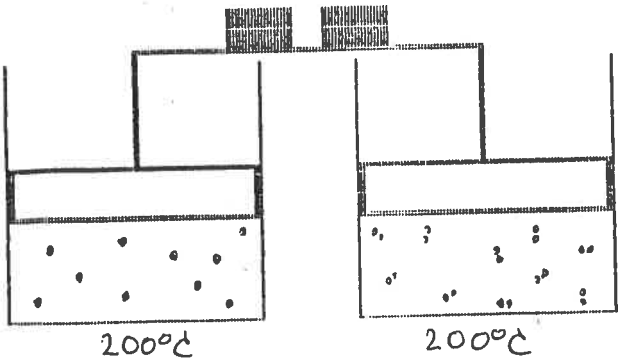


Figure 1A

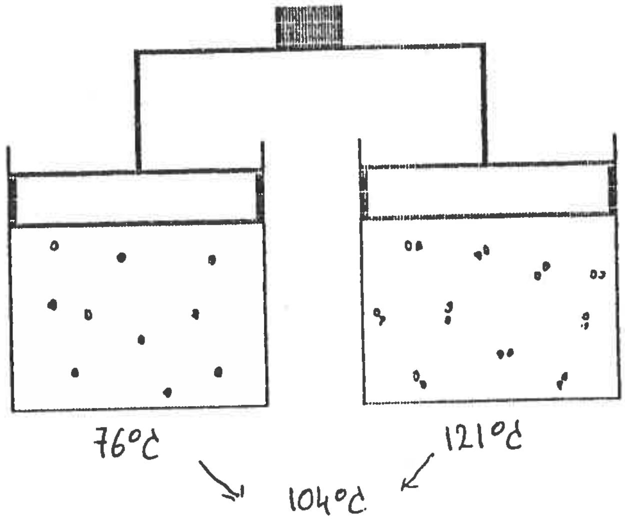


Figure 1B

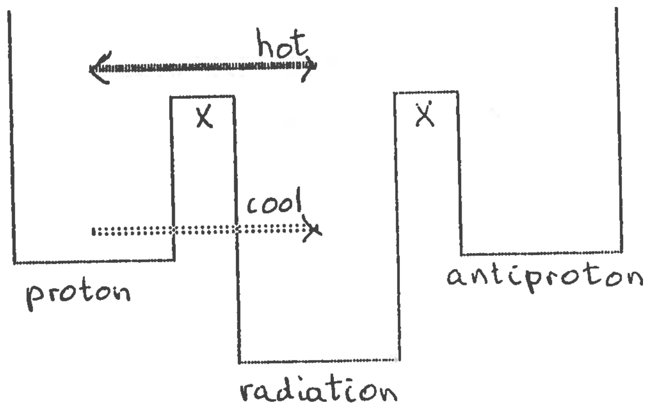
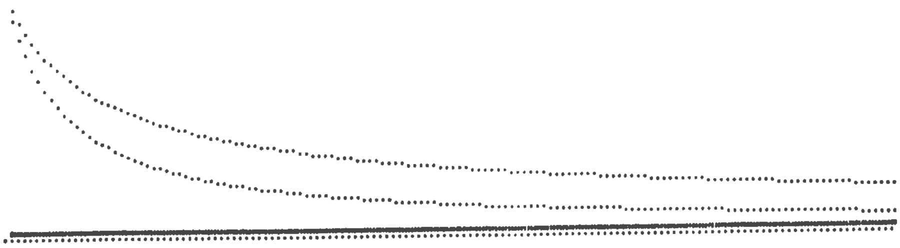
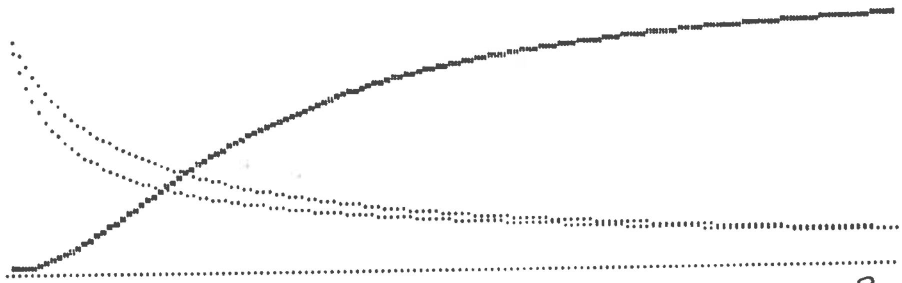


Figure 3



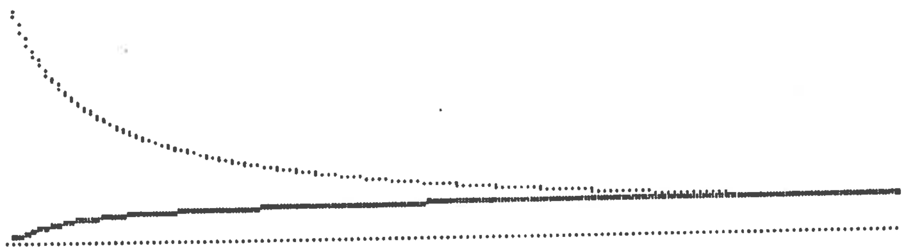
a = 0

Figure 2A



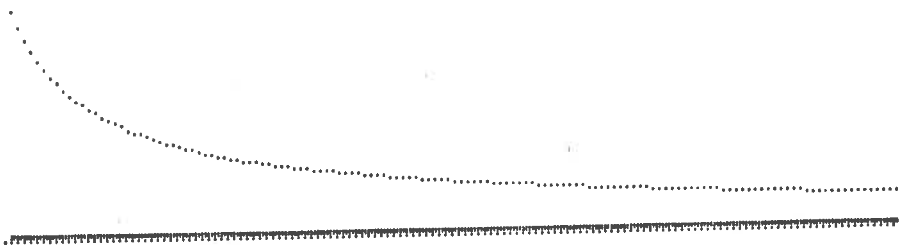
a = 3

Figure 2B



a = 30

Figure 2C



a = ∞

Figure 2D

slight chance of leakage from the electric trap is that the unstable two-proton system (^2He) suffers a radioactive beta decay before falling apart:

$$p^+ + p^+ \rightarrow (^2He) \rightarrow \begin{cases} p^+ + p^+ \\ \text{heavy hydrogen} + e^+ + \text{neutrino} \end{cases}$$

Heavy hydrogen is already an efficient nuclear fuel (burned in stars and used in hydrogen bombs). From this point the nuclear build-up may run to helium and later towards iron. But the first bottleneck slows nuclear fusion chain reactions from microseconds to billions of years. The small chance of the radioactive decay (the weakness of this interaction) makes the solar power station to work through billions of years, offering time for biological evolution on nearby planets.

Let Life Be!

Earth has been formed in an environment far from thermal equilibrium. In the hot Sun the overcooled nuclear hydrogen leaks through the electric barrier to heavier elements, dissipating the liberated energy into space. A fraction of these energy quanta reaches the luke-warm Earth. The sunlight is captured by photosyntesis and it is stored in organic molecules like sugar.Plants, animals, people live by dissipating the energy canned in organic molecules.

The surface temperature of the Sun is 6000 K,it radiates visible light. A fraction of the emitted energy hits the Earth,warming it to the surface temperature 300 K. The energy content of the Earth is does not increase steadily, because the same amount of energy is radiated into the cold outer space in form of infrared light, corresponding to the surface temperature of 300K. This means that the Earth gains energy in form of visible photons and it looses the same amount of energy in form of infrared photons. The infrared quantum is 20 times smaller,therefore the number of emitted photons is 20 times larger than the number of absorbed photons. The entropy (disorder) of radiation is proportional to the number of photons, therefore the Earth radiation carries away more entropy than what arrives from the Sun. The energy flow can vash away the surplus disorder from Earth.Decreasing entropy means increasing organisation.The steady disequilibrium enables the formation and spreading of living structures on our planet.

John von Neumann has proved mathematically that structures complex enough may become able to reproduce themselves. Reproduction has opened a new chapter in cosmic history. Let us consider a realistic structure (say,blue-green alga) which reproduces itself (by making use of sunshine) in about 60 minutes. In 5 hours (300 minutes) one gets 5 generations=2^5 exemplars. In 50 hours (about two days) one gets 50 generations=2^{50} exemplars. But in a noisy environment not all copies will be perfect. Random molecular collisions may produce misprints. A defect copy needs longer time, say, 75 minutes for reproduction. In 5 hours this gives 4 generations=2^4 copies, in 50 hours 40 generations=2^{40} copies! Misprints are eliminated by natural selection.Individuals decay and die, but the race does not age.

Let us assume that the environment changes(getting more sunshine or new chemicals in the pond...). By chance a misprint looses a segment of DNA which is not needed any longer in the new environment.Earlier time this mutation would have been lethal,but now the truncated DNA manages to copy herself in 50 minutes. In 5 hours this means 6 generations=2^6 copies. In 500 hours she produces 60 generations=2^{60} exemplars. Thousand times more than the original one! Life is like a folksong: it does not have a composer but a history of evolution.All misinterpretations are quickly forgoten but all improvements will be remembered.

The Last Judgement

The world experienced a resurrection from heat death: it entered transient periods of disequilibrium. Will it return to heat death again and when? This question is a subject of intensive study today.

Our Universe is about 16 billion years old. It is made mainly of thermal radiation (material realizing the maximum of disorder) but some surviving electrons, protons, nuclei, stars and planets add a disequilibrium contamination. These materials flow slowly toward the state of thermal equilibrium, by this trend they create a thermodynamical arrow of time.

Nuclear matter will be transformed to iron; stars become white dwarfs, neutron stars, black holes in $10^{10}-10^{20}$ years.

Protons may decay into positive electrons and radiation; stars and planets may crumble away through X or quantum gravity tunnelling in $10^{30}-10^{60}$ years.

Negative electrons (left over by decaying atoms)and positive electrons (from proton decay), massive neutral particles may collide and annihilate to radiation in $10^{40}-10^{60}$ years, if they remain bounded in clouds.

Lone (star and galaxy sized) black holes decay after 10^{100} years.

In case of massive but gravitationally unbound objects the random collisions compete with dilution in the expanding space. Will they be able to collide and fuse, in spite of their growing distances? Will collision time get shorter or longer than the age of the Universe while both grow beyond any limit? From human point of view,the fate of black holes seems to be the most interesting. If they do not clump, they are doomed to decay to radiation. But if they have a chance to collide and fuse before decaying,the increased mass prolongs their lifetime, which may prevent their complete degradation to radiation.If the later case is true, they never reach thermal equilibrium; the hot radiation of black holes may remain a source of free energy in the cold space for eternity.

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