THE UNIVERSE AS THE EARTH'S ENVIRONMENT

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Were the Earth a little pebble of one millimeter in diameter, the presently observable universe would extend to a billion (10^9) times the size of the true Earth. The vastness of the universe shows us that most of the direct influence upon our planet is likely to come from the nearby regions of the universe, in particular from the Sun and from objects in our planetary system, also called the solar system. High-energy cosmic rays—streams of charged high-velocity particles—nevertheless originate in rather distant active objects. The Earth has two protecting shields against fast charged particles: its magnetic field and its atmosphere. Electromagnetic radiation, from radio wavelengths to gamma rays, provides important clues about distant objects for the astronomer but is usually far too faint for any hazardous effects. Hard radiation from the Sun affects biological systems on Earth, and will be dangerous if the damage to the ozone layer proceeds too far. The ongoing impacts of dust particles and small rocks have limited effects because the Earth's atmosphere is, in this regard, an efficient protective shield as well. Statistically, however, on time scales beyond millions of years globally hazardous impacts are expected to occur. Such events strongly influence the evolution of biological systems on Earth. Considerable, albeit more localized, damage is expected on time scales of ten thousand years.

In addition to these direct influences, the Earth bears traces of the history of the whole universe. Atomic nuclei of light elements like helium were formed in the first minutes

of the universe. The nuclei of heavy elements in our bodies and in the Earth’s crust were assembled in the hot furnaces of stars at temperatures of hundreds of millions or billions of degrees. The human imagination is inspired by the enigmas of the universe and many societies are strongly influenced by their views of the world. Such wide perspectives might encourage us to treat our own subworld—the Earth—more respectfully.

1. Introduction

The Earth is the primary theme of this Encyclopedia. In rough numbers, the Earth is a relatively solid globe nearly 13 000 km across, which is orbiting on an approximately circular path with a speed of about 30 km/s at a distance of 150 million km around a body a hundred times larger than itself, called the Sun. The Sun is three hundred and thirty thousand times more massive than the Earth, although it is a hot gaseous ball with a temperature of 16 million degrees at its center. Towards its surface, the temperature gradually decreases to a few thousand degrees. The Sun is the “power plant” which feeds biological systems as well as weather and climate systems on the Earth with energy supplied by its radiation. Specific features of its radiation spectrum stimulate plant growth and animal metabolisms. In the long term, terrestrial systems are sensitive to variations in the solar output.

For millennia, and until a century ago, people held the view that the universe is a glorious, majestic, and peaceful system while violent events occur only on the surface of the Earth. This is the impression one obtains when one looks up to the sky on a moon-less night away from artificial light. This naked-eye view is misleading because one essentially sees only a narrow “thermal” part of the spectrum of, at best, a few thousand mostly stable stars. These are, although being in our neighborhood in cosmological terms, practically at infinity for the unaided eye.

Astronomers register information from objects that even have a *present* distance of $\sim 10^{26}$ m. This can be taken as the size of the *observable* universe. The size of the Earth of 10^7 m is negligibly small compared to the universe. However, when talking about distant objects one should note that their observed light was emitted when the object was closer to us than it is now. This is due to two foundation stones of modern cosmology: (i) the Universe is expanding, i.e. major objects like field galaxies and galaxy clusters are receding from each other; (ii) the velocity of light (and the only other form of electromagnetic radiation) is finite and obtains the value 299 792.458 km/s (in practice one can often use the value 300 000 km/s= $3\ 10^8$ m/s, which exceeds the exact value by only 0.07 %).

2. What the Night Sky Tells Us

Our eyes detect light that falls on the pupils. Light is a special form of electromagnetic *radiation* to which the eye is sensitive. Stars usually emit light in all directions. Of this light, only a narrow bundle falls into each of our pupils. Therefore, our eyes can only detect relatively bright stars. To detect and measure the radiation from fainter objects, astronomers build “artificial eyes,” called *telescopes*, with entrance pupils as large as they can afford (the “pupils” of the largest current telescopes have diameters of ~10 m).

In good conditions (clear dark, moon-less night) and with unaided eyes adapted to the darkness (i.e. for half an hour) about five thousand stars could be seen. With a simple 7 x 50mm binocular, a patient observer might count five million stars over the sky. In addition, there will be a number of nebulous objects that belong to various species to be disentangled by bigger telescopes. Within the reach of 10m-class telescopes or the Hubble space telescope are tens of billions of galaxies, gigantic star systems of their own. Most of them cannot be resolved and have not even been catalogued yet, but the analysis of the light of a fair sample of them tells us that many contain between tens and thousands of billions of stars.

Most of the point-like objects seen by the naked-eye observer (actually those that appear to “twinkle”) are *stars*, which are frequently grouped in areas of the sky called the *constellations*. These groupings are popular but of little value to the professional astronomer because the stars in a constellation usually have no relationship in space. The distances of the stars are so great that a convenient unit is a light-year, i.e. the distance traveled by a ray of light at a speed of 300 000 kilometers per second in one year (1 light-year = 9.46 10^{12} km). The nearest star known beyond the Sun is called Proxima Centauri at a distance of about 4 light-years.

Our eyes cannot perceive such a vast distance. We have no sense of the distances of the stars, so we obtain a wrong impression of the universe compared to that of a landscape on Earth to which our eyes are adapted. On Earth we obtain an impression of “depth in space,” of the relative distances of objects, thanks to our two eyes. The two eyes receive two different pictures from a particular object, which are combined in our brain to yield an impression of the distance of an object. At distances that are very large compared to the separation between our eyes, we become unable to “see the depth of space.”

Astronomers have devised a way of measuring the distances of stars: they enlarge the separation-distance of their artificial “eyes” (telescopes) to 300 million kilometers by taking one picture when the Earth is on one side of the Sun and another, half a year later, when the Earth is in its orbit on the other side of the Sun. A comparison of the images leads to reasonably accurate stellar distances up to about 300 light-years. Astronomers have learned to explore the universe to the present limits of 10 to 20 billion light-years by a number of distance-measuring methods (mostly by identifying standard objects with calibrated intrinsic brightness or size) that are built upon each other and combined with theoretical models.

For our eyes even the four-light-years distance of the nearest extra-solar star is indistinguishable from infinity. Thus, all stars appear to be at infinite distance, and our eyes are unable to detect their motions. This is the reason why constellations like Orion, the Great Bear (of which the Big Dipper is the most conspicuous part) or the Southern Cross do not appear to change. Occasionally, the stars are called “fixed stars” due to this property. Constellations may keep their basic appearance for thousands of years so that many names could simply be adopted from the antique descriptions. However, by carefully comparing photographs taken many years apart astronomers have measured the motions of numerous stars. Hence, “in the very long term” constellations will change. The Big Dipper is a famous textbook example that will look rather different in a hundred thousand years.

In other words, it is simply the smallness of the separation-distance between our eyes and the brevity of our lifetime compared to the true scales of the universe, which gives us the misleading impression of a majestically static world. Also, stars in a constellation should in general not be considered to be members of a coherent group. Constellations are mere *apparent projections* on a “celestial globe,” and we cannot tell from these projections the true distances their stars are at (this does not rule out the occasional coincidence that apparently close stars are close neighbors in space as well).

In addition, our eyes provide no clue about the true nature of these apparently luminous point-like objects called stars. Their nature has been revealed via sophisticated analyses that involve decomposing their light with spectrographic and photometric devices. Observing the stars at infrared or x-ray wavelengths has considerably extended our knowledge of their outermost shells. Stars have been found to be gigantic gaseous balls like our Sun, many cooler on their “surface,” others hotter. Depending on the type of the star, its surface temperature can be between a few thousand and several tens of thousands of degrees. In their centers, temperatures usually range from millions to the order of ten million degrees but may be much higher during short phases in the evolution of a star.

Thousands of years ago, careful observers already noted that in addition to the “fixed stars” there are “wandering stars,” which slowly change their positions relative to the pattern of the constellations. Depending on the object and the time, the positional variation becomes obvious after days, weeks, or more. Mankind needed several thousand years to develop a mathematically-formulated theory which explains and describes these motions to a high level of accuracy (Isaac Newton, 1642–1727).

Astronomers of the antique world noted that the wandering stars or planets are only to be found within a strip of constellations called the *zodiac*. An old division of the zodiac into twelve constellations does not exactly fit the current convention about the borders of constellations adopted by the International Astronomical Union. However, constellations named in the same order as the *zodiacal signs* of the astrologers are still in use along the zodiac. From the antique world until the eighteenth century five planets named Mercury, Venus, Mars, Jupiter and Saturn were known to be variously seen at changing positions within the zodiac. Interestingly, the Moon too was found to move through the zodiac, actually as the fastest wanderer. Relative to the stars, the Moon changes its position within 24 hours by about 13°.

Antique astronomers also noted that, in the darkness just after sunset, a zodiacal constellation always appeared near the setting point. Over the year, all twelve of these constellations appeared there, so that it was clear that the sun moves through the whole zodiacal strip within one year. Because in daytime we look towards the Sun, the night sky also has to change during the year. Let us slip into the mind of a sky watcher three thousand years ago. He (or she) is used to seeing the seasons in the night sky so that it is quite natural to relate celestial events to events on Earth. The sky is a calendarium and timekeeper. He/she sees the daily position changes of the moon in the zodiac. The only other major movements to be seen are those of the Planets within the zodiac. Consequently, for this person the zodiac is the most important part of the sky and the events within it are naturally related to events on Earth.

Thus, the birth of *astrology* in the antique world may be understood as the reaction of the human mind and psyche to what the typical observer saw. Present-day astronomers consider astrology a superstition because they now understand the simple reasons for the motions in the zodiac and, aided by their gigantic telescopes and instruments of analysis, they see violent movements and exciting processes in all directions toward the celestial sphere, not restricted to the zodiac. We gave this lengthy introduction in order to show how people saw the universe as our environment in history. One might ask why astrology has survived until the present day in journals and newspapers of the western world although the old reasons should not carry weight anymore. This is probably due to an intrinsic desire that humans have to know more about their future, and a consequence of widespread astronomical illiteracy.

In the era of telescopes, three additional optically faint Planets were discovered (Uranus in 1781; Neptune in 1846; Pluto in 1930). The question remains why the Sun and the Planets move through the zodiac. The apparent motion of the Sun is a reflex of the orbital motion of the Earth around the Sun. As seen from the Earth, there are stars at practically infinite distance (making up a zodiacal *constellation*) behind the Sun along its general direction. Seeing a star means that light reaches our retina along the *line of sight* from the star. To think in terms of the concept of "line of sight" is a convenient way to understand the apparent projections occurring in astronomy. When the Earth moves within its orbit for one month the line of sight towards the Sun changes its direction by 360°/12 = 30°. If the whole 360°- zodiacal strip were divided into 12 equally wide constellations then the Sun would be in front of a different zodiacal constellation every month. The *zodiacal signs* of the astrologers are a remnant of such thinking. However, they no longer agree with the actual position of the Sun because the Earth's axis has changed its orientation in space during the last two thousand years.

The planets and the Earth's moon appear in the zodiac because their orbital planes coincide with that of the Earth within a few degrees (ignoring the "outsider" Pluto). Also, the zodiacal light, a feeble glow visible in excellent conditions after sunset, appears along the zodiac. It simply consists of sunlight reflected by the dust concentrated in the plane of our planetary system. The strip of the zodiac—considered as somehow magical—simply reflects the fact that the Solar System is disk-like.

Mankind was plagued for thousands of years by the staggering fact that planets, after having moved in one direction in the zodiac, could turn and move backwards for some time (retrograde motion). Models devised by thinkers of the antique world used "circles on circles" (epicycles) to describe this behavior, with the Earth at the center of the world. In a Sun-centered model, in which an inner planet moves faster than an outer planet, an apparent retrograde loop motion can be easily explained by constructing the line of sight "Earth to outer planet" for a number of time steps, as is shown in elementary textbooks. The line of sight changes direction when the Earth "overtakes" the planet.

There are, however, more questions behind these simple projection games: for example, *why* is an inner planet faster than an outer planet? The answer can be traced back to the concepts of physics as devised by Isaac Newton (1642–1727). Briefly speaking, the attractive *force* exerted by the Sun is larger for an inner planet, because it is closer to the

Sun. In Newton's physics, this force has to be compensated by an *inertial* force, the centrifugal force, which is larger at faster orbital motion. Some people argue that this is not an explanation, only another concept to replace the first. However, the strength of the *second* concept is that it can be successfully applied to numerous other situations—it *unifies* the phenomena observed. Science is still heading for unification, albeit on an apparently "higher" level.

Briefly, the solar system consists of the Sun in its center, with nine planets in orbit around it. In order of increasing mean orbital radius (in brackets after the name) there are Mercury (0.4), Venus (0.7), Earth (1.0), Mars (1.5), Jupiter (5.2), Saturn (9.6), Uranus (19.3), Neptune (30.1), Pluto (39.9) (given in units of the Earth's orbital radius = 1 AU = 1.5 10^8 km = 8 1/3 light-minutes). Many planets have moons, in orbits around them. In addition to these planets there are *numerous smaller bodies* like minor planets, including asteroids, larger meteoroids, and small dust particles.

3. Matter and Radiation in the Universe

To understand the impact of the Universe on the Earth we have first to know the stuff out of which the material in the Universe is composed. In the planetary system, which has a size of a few light hours, many solid objects are flying ("orbiting") around. In the lower size-range we have tiny dust particles (size 1 to 100 micrometers), micrometeoroids that cause the zodiacal light by scattering the light from the Sun. However, the spectrum of sizes of meteoroids extends to those of rocks and even chunks tens of meters across. At such large sizes some workers in the field would call them asteroids. Many meteoroids may be fragments left over from collisions of asteroids (or minor planets), which range in size up to nearly 1000 km. Other solid objects in the planetary system like the inner planets (from Mercury to Mars) or satellites (moons) of planets have no direct impact on the Earth.

Considering the total matter content of the Universe, solid objects are extremely rare. Even in our own planetary system, the Sun's material is in a kind of gaseous state, or more precisely, plasma state. Nearly all the visible matter in the Universe is in this kind of state. To understand the nature of the different states of matter we shall briefly digress to atoms, ions, and their constituents and the bonding of atoms.

Chemical elements are made of atoms, which consist of a nucleus and a shell of electrons. About ninety percent of all atoms (or ions) in the Universe belong to the element hydrogen. The hydrogen atom is the simplest of all atoms with a single positively charged particle, called the proton, as the nucleus and a nearly two-thousand times less massive, negatively charged particle, called the electron, making up the shell. Nearly all of the remaining ten percent of all atoms in the Universe belong to the element helium. The nucleus of the helium atom consists of four particles, two protons and two electrically neutral particles of similar mass as the proton, known as neutrons. To balance the nuclear electrical charge, the shell of the helium atom consists of two electrons.

The total abundance of all atoms heavier than helium and hydrogen makes up, in typical cosmic matter, only 0.14 percent of the total number of atoms (but 1.9 % of the total mass). These heavy atoms consist of nuclei with more than two protons. The number of neutrons in the nucleus may differ from that of the protons. The number of electrons in the shell of a neutral atom coincides with the number of protons in the nucleus. After having released one or more electrons from the shell, one has a positive ion of the element in question (the element is identified by the nucleus). Negative ions (with, for example, an electron added) are rare but can play an important role as absorbers of radiation in cool stars.

Frequently, cosmic gases are ionized, and there is a dynamical balance between stripping off electrons and the process of recombination in which electrons are caught in the shells of an ion. Though charges are separated, such ionized gas is usually electrically neutral when averaged over a volume element that is not too small. This kind of state of matter is called the plasma state. Below, the general term gas will also be used in cases when plasma is meant.

Atoms of a gas can be ionized by collisions (collisional ionization) with fast particles (usually by electrons) or by collisions with energetic photons, i.e. “radiative particles” (photoionization). In contrast to normal particles, photons have no mass, but like normal particles, they have momentum and energy, which can be transferred via collisions. A star emits photons (radiation) with energies in a wide range. However, the hotter the star the more energetic is the average photon emitted. Stars with surface temperatures above about 30 000 K are hot enough to efficiently ionize hydrogen gas in their vicinity by their radiation. When electrons are caught by the protons or ions, they may cascade down some of the energy states allowed by quantum theory. Much of the released energy is converted to photons in the visual part of the spectrum, providing the ionized nebula with a feeble glow. On a clear dark night, the glow of the Orion nebula, a photoionized gas cloud located in the sky in the “sword” of the constellation Orion, can even be recognized with the naked eye. The technical term for such an emission nebula, photoionized by the radiation of young stars, is HII-region.

For the astrophysicist, temperature in a gas is a measure of the average speed of chaotic particle motions (in a state of at least local equilibrium). Thus, at very high temperatures, collisions with electrons that have correspondingly high speeds leads to appreciable collisional ionization. Tenuous gas between the stars and in the halos of galaxies with temperatures of millions of degrees is in such a state. The high temperature in cosmic gases is frequently traced back to shocks in which strong directed streaming motion—as in the sound-speed-exceeding expanding shells from stellar explosions—is converted to chaotic “temperature motion.” Gas that is photoionized usually only has a temperature of about 10 000 K because part of the kinetic energy of electrons is withdrawn by certain ions that absorb it in inelastic collisions and convert it to radiative energy emitted away. Shock-heated and ionized gas is distributed over a wider temperature range, with peak temperatures usually much higher than those attained in photoionized gas.

However, there are many locations in the universe without strong motions or strong radiation fields in their environment so that cool gas with temperatures of tens of degrees Kelvin (above absolute zero) can survive. Clouds of neutral hydrogen with the cosmic admixture of helium and heavier elements can be observed by astronomers via their typical radio radiation in many galaxies. If the gas is very cool and dense and cosmic dust particles are available as a catalyst then hydrogen atoms are more likely to combine pairwise to form hydrogen molecules. From mixtures of atoms of the heavy trace elements, a variety of molecules can be formed as well. The molecules are condensed in gigantic cloud-like aggregates. Such molecular clouds are very important for the evolution of matter in the universe, because these are the likely sites of future star formation. Our Sun itself, together with the solar system, was once born within a molecular cloud. Astronomers have detected rather complicated molecules in molecular clouds. For example, such compounds as ethanol (the digestible form of alcohol), formic acid, or cyanodiacetylene are not uncommon. This shows that basic organic compounds are common in the universe. However, samples of living systems require more special conditions so that we cannot reliably guess their frequency.

Liquid water is needed for living systems to form. In gases the molecules are relatively far apart, in fast motion, and they therefore exert negligible or only mild forces on each other. In liquids they are tightly packed and in closer interaction, but the individual molecules can still move relative to one another. Liquids exist on and in various planets, under the appropriate conditions of pressure and temperature. Life appears to need liquid water to grow; even in ice and snow a liquid fraction is required. When looking for life on other planets, planetary scientists first look for traces of water. A water molecule H_2O resembles a clothes hanger arranged in the sequence H–O–H. Chemical bonding of the original electron shells makes the centered O atom attract the electrons from the outer H atoms so that the center is more negatively charged and the outer ends are more positive. This particular arrangement makes water a good solvent, easily splitting apart ionic bonds of solids.

Solids consist of molecules or ions more rigidly locked in place, often in a rather regular crystal lattice. Solids are rather rare in the Universe because—under common temperatures and pressures—the abundant elements hydrogen and helium cannot solidify and heavier elements contribute only about 2 percent to the total mass. Solids occur, as in our solar system, in planetary systems and in the form of tiny dust particles yielding a percent contribution (by mass) to the interstellar gas. There are also ices, e.g. on planets and abundantly in the nuclei of comets. Solid water can possess at least eight different crystalline states. However, under the commonly low-pressure space conditions water ice is likely to form an amorphous solid rather than large regular hexagonal arrays.

In agreement with observations, cosmic dust occupies a plausible one percent fraction of the mass of the interstellar medium. Despite its apparently low mass contribution, dust has considerable effects on the transmission of light, frequently hampering the reconstruction of the true structure of large cosmic systems. In interstellar clouds, most of the dust grains are slightly smaller than the wavelength of visual light and thereby absorb and scatter blue light more efficiently than red light. This leads to a reddening of the light of stars beyond an intervening interstellar cloud. The longer-wavelength photons of infrared or radio radiation traverse dusty clouds even more easily. However, the absorption of ultraviolet and visual radiation can frequently heat dust grains to temperatures that make them re-emit the energy via infrared radiation. For instance,

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Biographical Sketch

Hartmut Schulz was born in Kiel in Germany in 1948. In 1974 he acquired the academic degree "Diplom-Physiker" at the University of Kiel where he also obtained a Doctorate degree in Astronomy in 1977. After a post-doctoral year in Kiel he worked as astrophysicist at the Max Planck Institute of Astronomy in Heidelberg during the erection of Calar Alto Observatory in Spain until 1983. Subsequently he taught and conducted research at the Planetarium of Wolfsburg and the Universities of Bonn, Tübingen, and Bochum. In 1995 he obtained the "Habilitation" in Bochum where he is still teaching as "Privatdozent" (University lecturer). He has carried out astronomical observations at various telescopes in South Africa, Spain, and Chile, and analyzed data from the Hubble Space Telescope and the Rosat x-Ray satellite. In 1990 and in 1997 he taught as Visiting Professor at Dartmouth College, New Hampshire. His research extends from topics like the mass distribution of white dwarf stars, and radiation cones in active galactic nuclei, to the nature of infrared galaxies and relativistic cosmology, and is documented in over 80 original scientific articles and about the same number of scientific reports.