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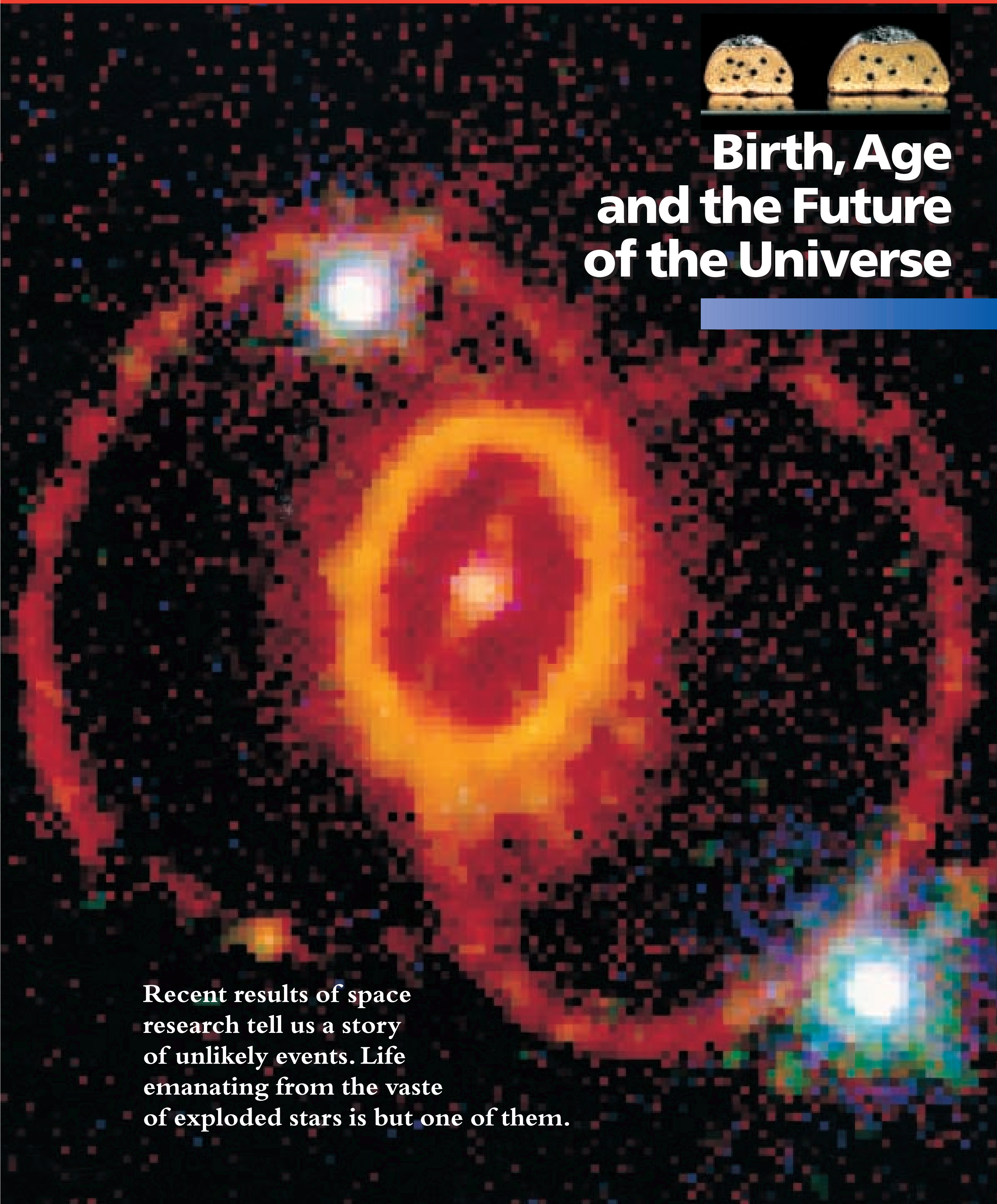

Birth, Age and the Future of the Universe

Recent results of space research tell us a story of unlikely events. Life emanating from the vaste of exploded stars is but one of them.

Editorial

We are here. There is no doubt about it. –

Research, however, has shown that life, our solar system and all the galaxies interrupting locally the voidness of space have been caused by tiny unbalances, which seem very unlikely a priori. Recent results of space research tell us a story of unlikely events.

This fascinating history of our universe was the subject of the key note address by Professor Gustav Andreas Tammann, Director of the Institute for Astronomy of the University of Basle on the occasion of the third anniversary of the International Space Science Institute on the 27th of November 1998.

It is with greatest pleasure that we devote this issue to Professor Tammann, who has actively contributed to the understanding of our universe over the past 40 years.

Hansjörg Schlaepfer
Berne, May 1999

Impressum

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Front cover
Rings of glowing gas encircling the supernova 1987A.
(Hubble Space Telescope, NASA/ESA, February 2, 1994)

Birth, Age and the Future of the Universe

G. A. Tammann, Director, Institute for Astronomy, University of Basle

Key note address at the third anniversary of the International Space Science Institute, November 27, 1998

The sciences have fundamentally changed the views of our world during this Century. They have brought a cultural revolution by affecting technology, medicine, civilisation and, perhaps most importantly, the thinking of men.

Man has explained the origin of all life, i. e. the energy source of the Sun which had remained a total mystery up to 1930. He has established a worldwide net of communication and transportation such that he partakes almost instantly in occurrences all over the world. Humans have left the Earth's gravity field and have seen that the Earth is round. The Moon has been occupied – so far temporarily – by men and the planets have been visited by spacecraft. The triumph of rational thinking has even brought an unprecedented 50-year period of peace in Western Europe.

For thousands of years the human life has been an interval of 40 years of suffering of hunger and freezing. Science has doubled its length and it is now expected to be painless, comfortable and pleasurable. At the end of this century man finds himself in a world which has been fundamentally changed by the sciences from what it was at the beginning of the Century, – and not only the world has changed but also man himself, – and were it just in physical size.

It may seem surprising that this radical change has been brought about by the sciences which are believed to progress step by step by a painstaking method dominated by mathematical logic and bare of fantasy. While it is true that all sciences proceed in minute steps, it happens once in a while that the understanding jumps suddenly on a higher level. A broader insight is gained, a new paradigm is born. These are the great discoveries which influence our understanding, thinking, and culture.

A few examples will be given in the following from the realm of astronomy. They are to illustrate how the scientist works on a gigantic mosaic that suddenly reveals a face or contour.

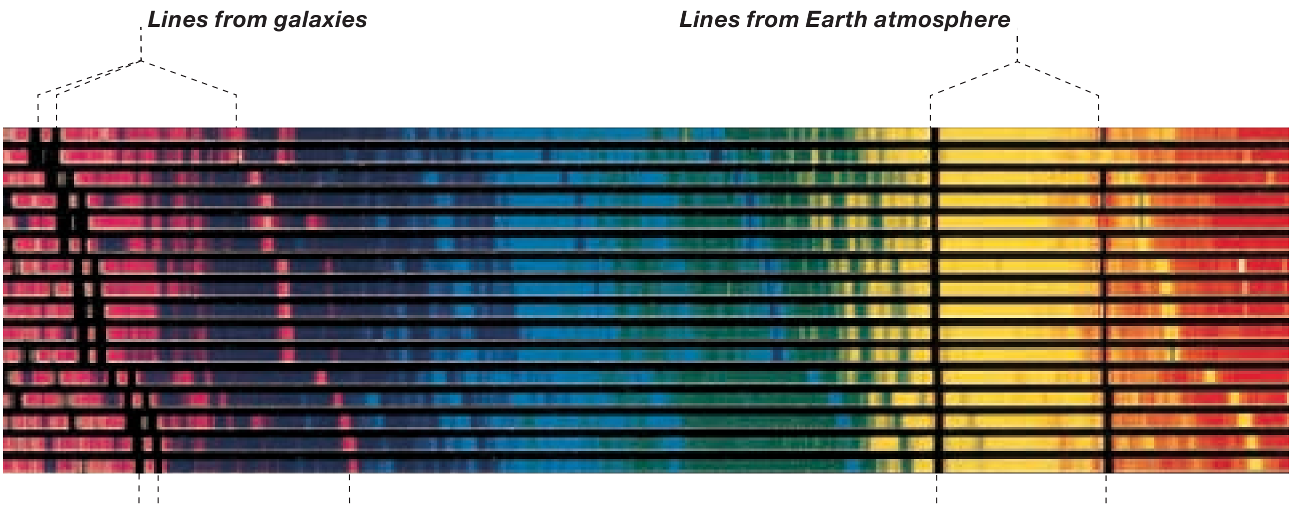


Figure 1. The spectra of 16 galaxies. They are perfectly aligned as seen from the lines originating in the Earth's atmosphere. However, the galaxy lines (originating from different chemical elements) are progressively shifted toward the red. This redshift effect is caused by the expansion of space stretching the light to longer wavelength. The different redshifts correspond here to recession velocities of 3000–16,000 km s^{-1}. (From P. Stein, Basle).

The expanding Universe

In 1912 Vesto M. Slipher took the first spectra of what was then called spiral "nebulae" (now known to be galaxies). It was a tedious process with small telescopes and slow emulsions. He found the spectral lines shifted toward the red **(Figure 1)** and he concluded correctly that the objects were hence receding from us, – yet faster than any known star in our Galaxy. The large recession velocities became a puzzle which many astronomers tried to solve. Finally Edwin Hubble, after having proved in 1925 that the "nebulae" are distant galaxies, consisting of hundredthousand million stars like our Milky Way, realised in 1929 that not only (almost) all galaxies move away from us but also that their velocities were proportional to their distances! **(Figure 2)** The picture was like that any raisin has in a growing yeast cake: all other raisins are moving away and the faster the further away they are **(Figure 3)**. Hubble concluded that the whole Universe was expanding like a yeast cake and that there must have been a time where the Universe was arbitrarily small. The Universe had a beginning, now known as the Big Bang!

Figure 3. A yeast cake as a model for the expanding Universe. As the cake increases in size the distances between the raisins become larger. Close raisins get separated by small (absolute) amounts, distant raisins by large amounts. The aspect is the same for *all* raisins. (Neglect the rim). The model has the disadvantage that one can oversee it instantaneously while the concept of simultaneity fails in the Universe (see page 5).

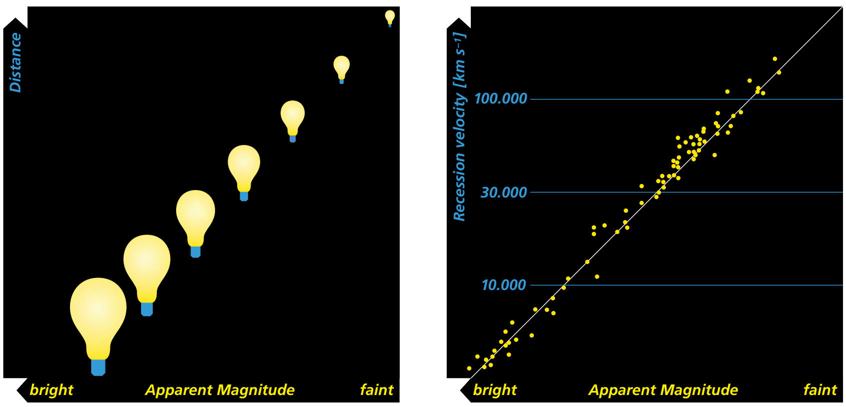


Figure 2. The demonstration of the linear expansion of the Universe. Left: Standard candles (e.g. 60 W light bulbs) get fainter as the distance increases. Right: The brightest galaxies in clusters of galaxies are good standard candles (note the relatively small scatter!). As they get fainter they must be more distant, but at the same time their recession velocities increase. (*Linear* expansion requires in this logarithmic plot a slope of 0.2, which is shown).

In the last seventy years the Big Bang has become a physical fact. The most distant galaxies have redshifts corresponding to *almost* the speed of light. Several independent experiments prove beyond doubt that the young Universe must have been tiny, extremely dense, and excessively hot.

The expansion of the Universe gives us a simple tool to determine its age. At a very early epoch all galaxies (or the matter or energy they were later made of) were compressed in one place. When the expansion began some were slowly carried away; they are today our neighbors. Others were carried away with high speed; they populate now our horizon. All had the same travel time, i.e. the age of the Universe. Therefore one must determine "only" the distance to one galaxy – or much better to many galaxies, which is technically not easy **(Figure 4)** – and divide this distance by the recession velocity. The result is nothing else but the expansion age of the Universe.

Measured redshifts and the corresponding recession velocities plus the best distance determinations give an expansion age of 14 (±2) Gigayears (1 Gigayear = 1000 million years). This time may appear long, but when one realizes that life began 3 Gigayears ago, that the oldest rocks on Earth have an age of almost 4 Gigayears, and that the oldest stars in our Galaxy were formed 12 Gigayears ago, one cannot but be impressed by the youth of the Universe. Imagine you take a very old rock in Greenland into your hand and it has almost one third of the Universe's age!

The expanding Universe revises in several ways our thinking. For instance, the fact that all galaxies are receding from us makes us falsely believe that the Big Bang has taken place *here.* In reality *any* galaxy, like any raisin in the yeast cake, sees *all* other galaxies (raisins) in recession. There is no preferred, absolute point in the Universe. Our thinking is unjustifiably egocentric. After some more thought (concerning the "edge" problem of the Universe) one realizes that the picture of galaxies travelling through space cannot be correct. In reality space expands and carries the galaxies along. This is perfectly reasonable with Einstein and is again exemplified by our yeast cake: not the raisins move apart, but the dough expands and increases the distances between the raisins.

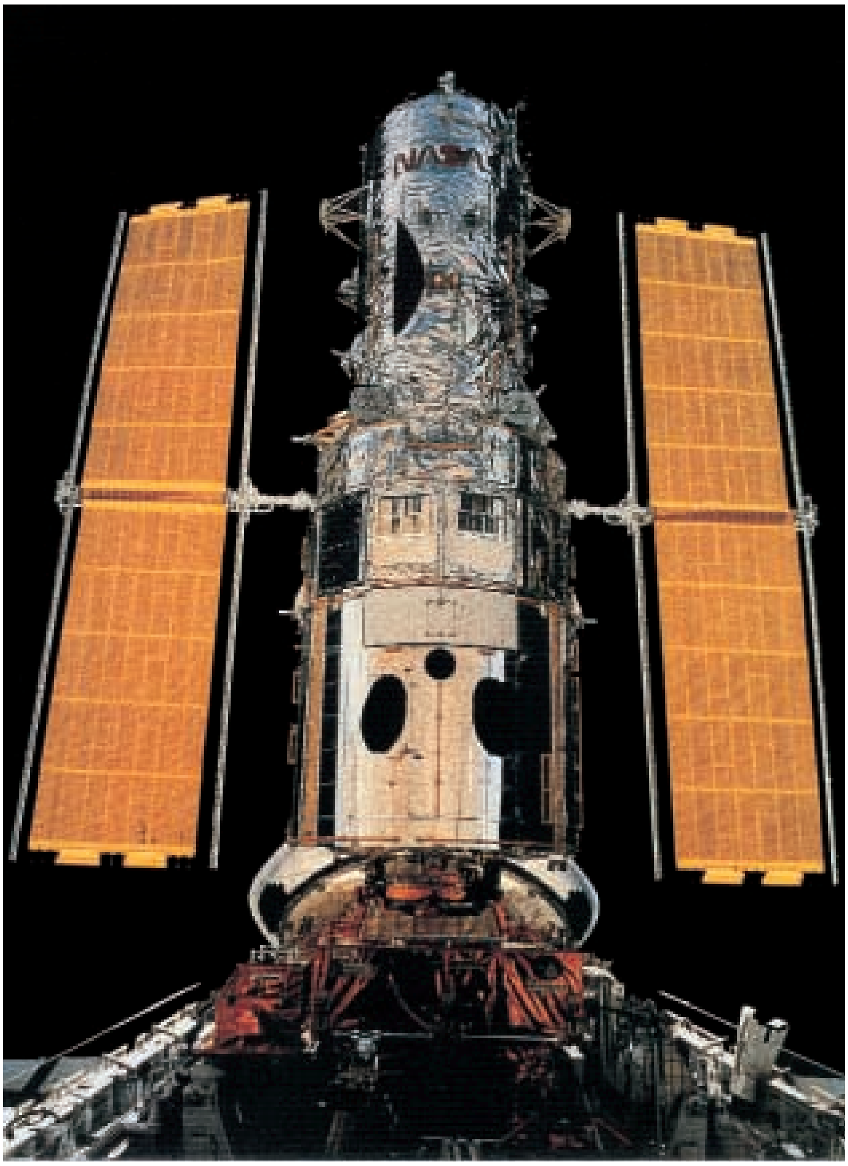


Figure 4. The Hubble Space Telescope has a mirror of "only" 2.5 m diameter, but since it orbits the Earth above the atmosphere it provides exceptionally sharp images. It has greatly helped to determine galaxy distances and hence to determine the expansion age of the Universe. The telescope was built and is operated by NASA with a 15% share of the European Space Agency (ESA). The telescope is here docked to the Space Shuttle during a repair mission involving the Swiss astronaute Claude Nicollier.

Evolution in the Universe

Still hundred years ago there was an embittered debate between creationists and evolutionists. Did God create the world as we see it today? Were the large erratic blocks placed by him into the midst of green meadows, or where they transported there by the ice? Do the fossils give clues to the evolution of life, or did God make the rocks including the fossils? But as correct as the evolutionists were, they could not answer the question where evolution began.

The starting point of evolution became clear only with the discovery of the Big Bang. At the beginning, an unthinkably small fraction of a second after the Big Bang, the Universe was unmeasurably hot and it contained nothing but immensely condensed energy. As it expanded and cooled the energy transformed into matter, first into exotic, short-lived particles, then at an age of $^{1}/_{10,000}$ seconds into protons and neutrons, i.e. the matter we know today. At that time the temperature had fallen to a few times 10^{12} degrees and the density had decreased to 1000 million tons per thimbleful.

The creation of matter is no trivial thing. When one produces matter from energy in the great particle accelerators, e.g. at CERN, equal amounts of matter and antimatter are produced. But the two constituents annihilate each other to form energy again. It therefore seems that the Universe cannot ever create lasting matter. However, there is a very slight unbalance favoring matter over antimatter. The excess of newly created matter is only one part in 2000 million. The bulk of all matter has actually been annihilated. Only the tiny excess matter has survived and is nowadays what we see as matter. The unbalance between matter and antimatter is called the symmetry breaking; it is still not fully understood. And yet it is decisive for our existence.

Hundred seconds after the Big Bang the temperature had dropped to 1000 million degrees and for the first time protons and neutrons could stick together to form the most simple elements, deuterium and helium and traces of lithium. Theory predicts that 24 percent of all matter was transformed into helium, and it is a triumph for Big Bang theory that one has never found a gas cloud in our Galaxy or other galaxies with less than this amount of helium. Also the observed abundances of deuterium and lithium agree well with theory. The chemical composition

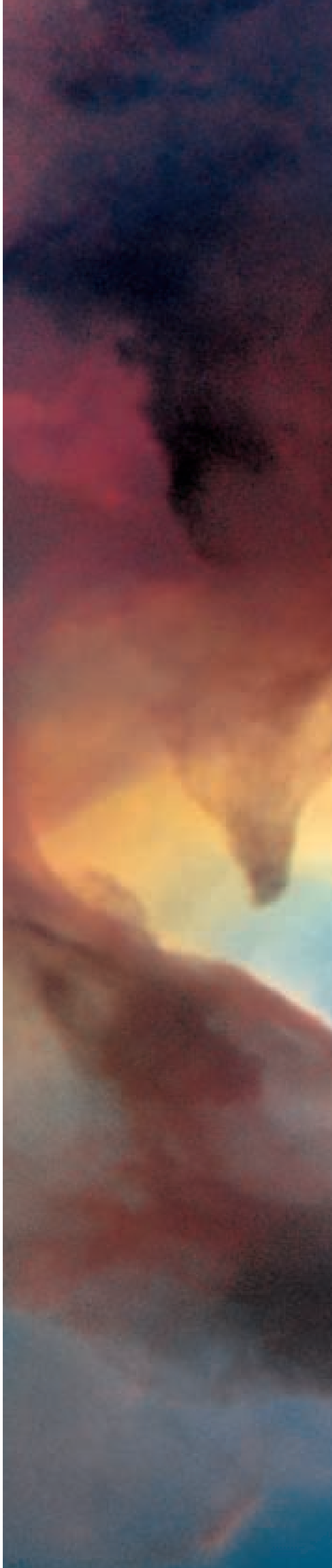


Figure 5. A part of the large "Lagoon Nebula" in our Galaxy (here about 1 lightyear x 1 lightyear). The bright hot star in the lower right ionizes and excetes atoms of sulphur, oxygen, and hydrogen which radiate at different wavelengths (here in false colors red, blue, and green, respectively). The heated gas is in tornado-like turbulence and triggers star formation in the surrounding cold, dark cloud of molecular gas and dust. This is a typical cradle of newly born stars. (Space Telescope Science Institute).

Figure 6. Structure formation has produced galaxies like this beautiful spiral (NGC 1232). The Milky Way seen from outside would offer a similar view. (Picture taken by the European Southern Observatory, ESO).

of these gas clouds is telling because they have yet experienced little chemical mixing and they reflect still today the primordial composition. The relevance of the abundances of the lightest elements for cosmology was first recognized at the University of Berne, and it is still an important research topic at ISSI.

The "primordial nucleosynthesis" of the lightest elements raises a fundamental question. Why was not *all* matter transformed into helium? In that case all "fuel" for later stars (which shine because they convert hydrogen [protons] into helium in their interior) would have been exhausted early on. The sky would have remained dark and life would have become impossible. The reason that most hydrogen (protons) has survived is that the neutron is more massive than the proton by 0.14 percent. Hence more energy is required to create a neutron and there are fewer of them. When all neutrons were used up the helium production stopped. Again we realize that life hangs on a thin thread, i.e. on the tiny mass difference between the neutron and the proton.

In its early phases the Universe was very simple; one says that it was in thermodynamical equilibrium. That means it was everywhere the same. The whole Universe could be fully described by a few numbers. One might now expect that the expanding Universe would just cool and thin out. Nothing interesting would ever happen.

The opposite is the case. That is, the Universe formed *structures.* There were regions where by chance more matter was than at others. In these dense regions gravity had its way to *locally* slow down the expansion and even to reverse it into a contraction. Gigantic, contracting clouds of hydrogen (and helium) were formed, which fractionated into smaller, still contracting clouds. The latter evolved into what we see today as galaxies **(Figure 6)**. The galaxies had spun up during their contraction, and their rotation protected them from further collapse. But individual cloudlets, still with thousands of solar masses, could continue to contract and form stars. The formation of stars is an *ongoing* process in galaxies **(Figure 5)**. New stars are born and old stars die continuously until all gas is used up. Some galaxies have already exhausted their gas supply; our Galaxy can still go on for a long time.

A contracting star heats up until its interior has reached a temperature of a few million degrees. At this moment a hydrogen bomb is ignited and hydrogen is fused into helium, a process which releases enormous amounts of energy. The energy protects the star against further contraction and lets the star shine. In the case of the Sun this energy is also the basis of all life.

Low-mass stars die as so-called White Dwarfs **(Figure 7)** when they have converted all their hydrogen into helium. More massive stars can then take regress to "burning" helium to carbon, oxygen and other more complex elements up to iron. The production of still more heavy elements does not release energy but costs energy. This energy can only be provided by the most massive stars when they die in the gigantic explosion of a supernova **(Figure 8)**. It is an unfamiliar thought that the gold on our finger was once produced in a supernova explosion.

Yes, all chemical elements in the Universe and on Earth have once been produced in stars. When stars die they eject part of their mass, either peacefully as a Planetary Nebula or explosively in a supernova. In this way some of the

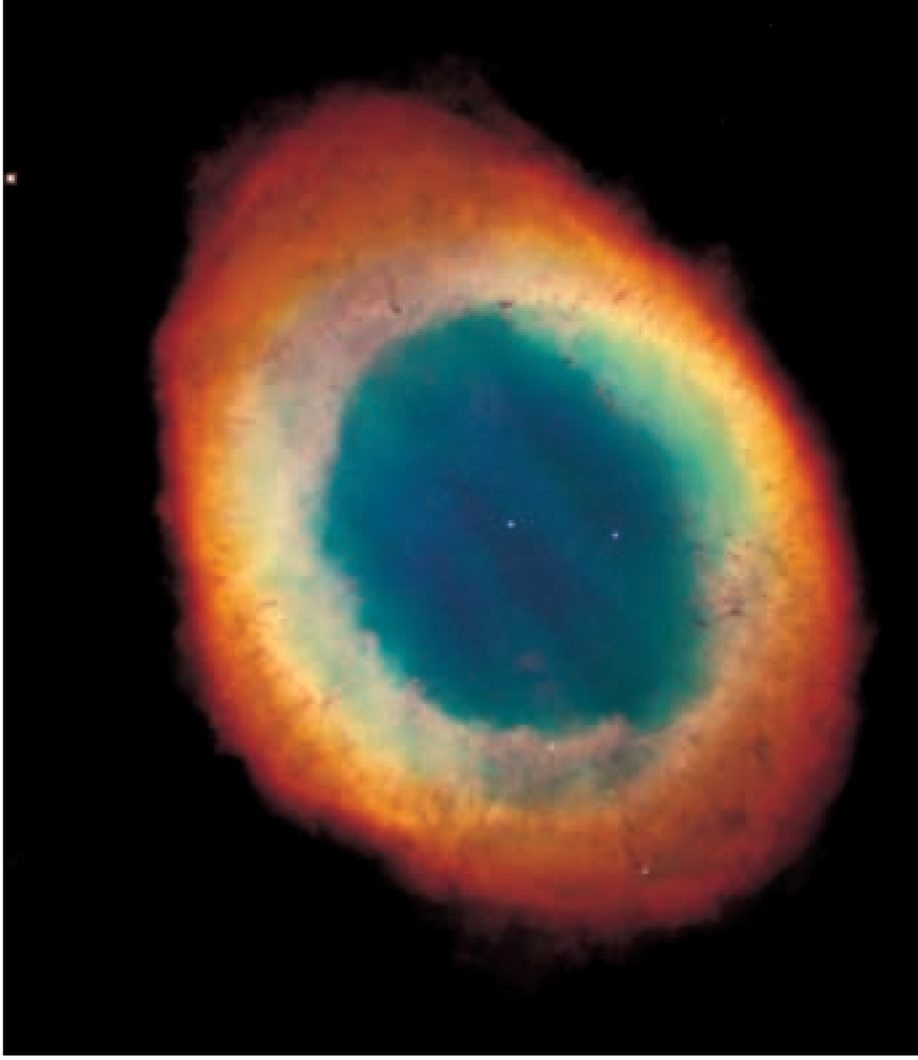
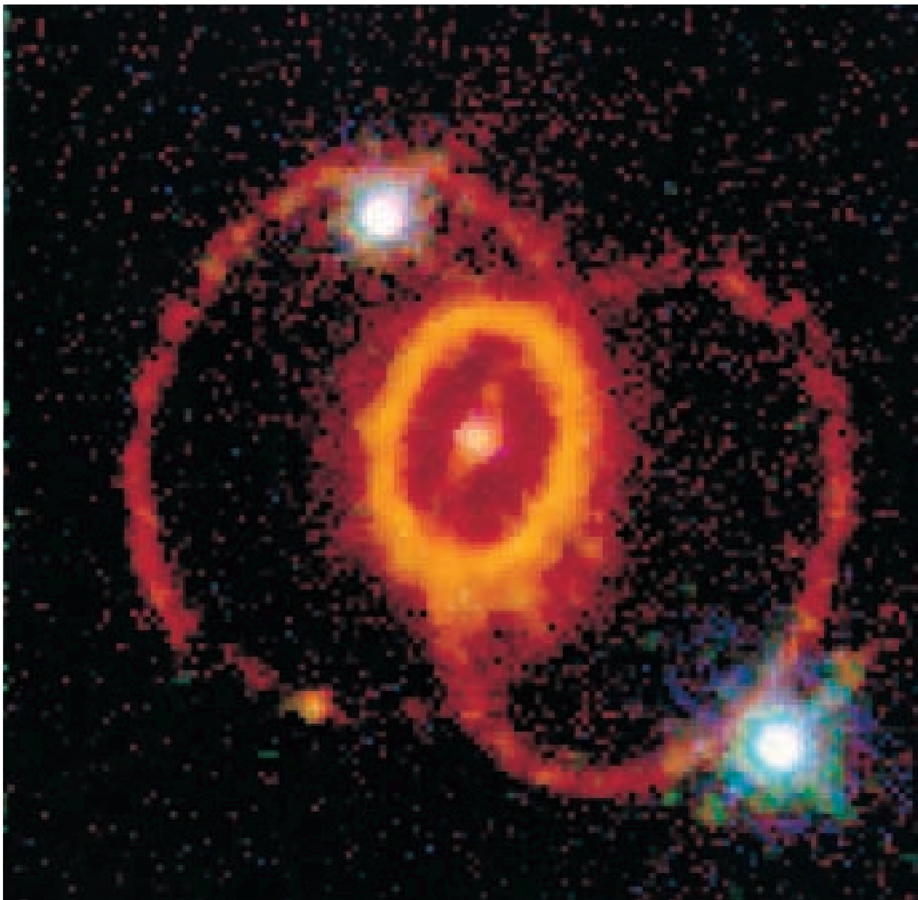


Figure 7. The Planetary Nebula in the constellation Lyra. The faint central star has lost its envelope which is enriched by the chemical elements formed during the lifetime of the star. The central star is only the left-over nucleus with a surface temperature of 120,000 degrees. It is going to become a White Dwarf.

Figure 8. The remnant of the supernova 1987A in the Large Magellanic Cloud, taken seven years after explosion with the Hubble Space Telescope. Large amounts of freshly formed heavy elements are expelled into the interstellar gas of the galaxy. Pre-ejected matter echoes the flash of the explosion.



chemically processed material comes back into the interstellar gas. Newly forming stars are in this way "contaminated" with carbon, oxygen, iron etc. When our Solar System formed 4.6 Gigayears ago all 92 elements were already present **(Figure 9)**. This was possible only because the most massive, chemically most productive stars are paradoxically quite short-lived, and most elements were actually built up long before the Solar System isolated itself from the interstellar gas.

The conclusion is that the chemical variety on Earth is possible only because previous generations of stars have produced all elements, except the primordial hydrogen and helium. We are made of stellar material.

The most puzzling point of this story is that the formation of structures (galaxies and stars) went so fast. The oldest stars in our Galaxy have ages of 12 Gigayears, i. e. they were formed within the first 2 Gigayears after the Big Bang. Computer models fail to form structures in so short an interval, unless one assumes that more than one half of all matter is not in form of protons and neutrons, but is "exotic". This so-called Dark Matter consists of unknown particles with unknown properties, but it seems unavoidable to explain structure formation. Great efforts are presently undertaken to detect this elusive form of matter. There are still things in the Universe we only can dream of.

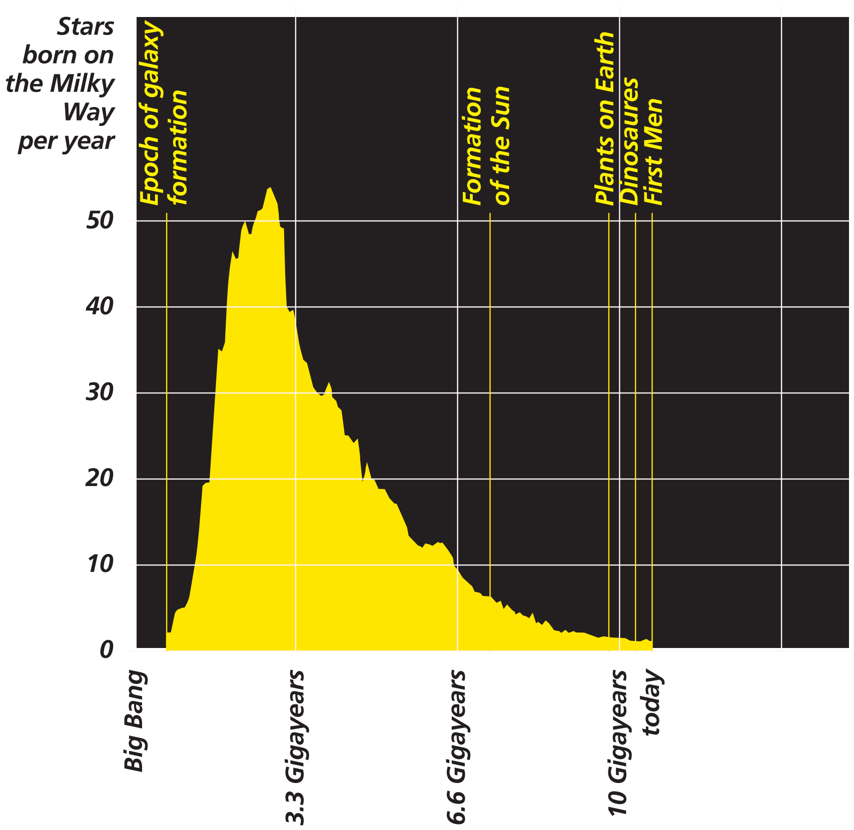


Figure 9. The star formation rate in the Milky Way in function of time. Most stars were formed about 3 Gigayears after the Big Bang. When the Solar System, including the Earth, was formed about 5.4 Gigayears later, all 92 chemical elements had already been formed in stars and expelled into the interstellar gas. This explains why the Earth is relatively rich in processed material. (From M.Samland, Basle).

The Astronomer as Perfect Historian

In the 1660's G.D. Cassini observed in Paris night for night the four Galilean moons of Jupiter as they revolved around the planet and disappeared and reappeared behind or in front of the planet's disk. As Galilei before him he hoped to find in this way a perfect clock which would have been of upmost practical importance for navigation. Yet he noticed irregularities: the predicted occurrences happened sometimes too early or too late by several tens of minutes. The puzzle was solved by Olaus Römer in 1677 who realized that the occultations occurred early when Jupiter was relatively close to the Earth and late when the planet was distant. This led him to one of the most fundamental discoveries of the millennium, i.e. the speed of light is *finite.*

We know today that the speed of light is c = 300,000 km s^{-1} and, according to Einstein, that this is the largest velocity possible because the light particles (photons) have zero rest mass. Any particle with mass can travel only slower. In particular this means also that no signal can be transmitted faster than with the speed of light. (So-called phase velocities, e.g. the movement of a shadow, can exceed c, but they involve neither mass motion nor signal transmission).

Figure 10. The Very Large Telescope of the European Southern Observatory (ESO) in the Atacama Desert in Chile where the observing conditions are optimal. With four 8 m-telescopes it will be the largest telescope in the world. The first 8 m-telescope is already successfully working. A major goal is to study the most distant (i.e. youngest) galaxies during the formation process.

Within human dimensions light travels *almost* infinitely fast. But over cosmic distances light is a slow messenger. It takes 8 minutes from the Sun to the Earth, 4 hours from Pluto, 10,000 years from a distant star in our Galaxy, and one million years from our nearest large neighbor galaxy, the Andromeda nebula. The light of the most distant known galaxies takes more than 10,000 million years!

This implies immediately that we can never have an instantaneous picture of the World. The information we receive here and now is staggered in time according to distance. Any object in the Universe gives us information about the appearance it had when it emitted the light we receive today. The time interval between light emission at the object and reception on Earth is obviously just the (distance-dependent) light travel time. Looking at (very) distant galaxies means therefore to investigate (very) *young* galaxies. The evolution of galaxies can therefore directly be observed.

The enormous progress in the construction of modern telescopes in space and on the ground **(Figures 4 and 10)** is therefore driven not only by the aim to use them as "space ships", bringing distant objects closer to the observer, but also as "time ships", bringing past events into the present.

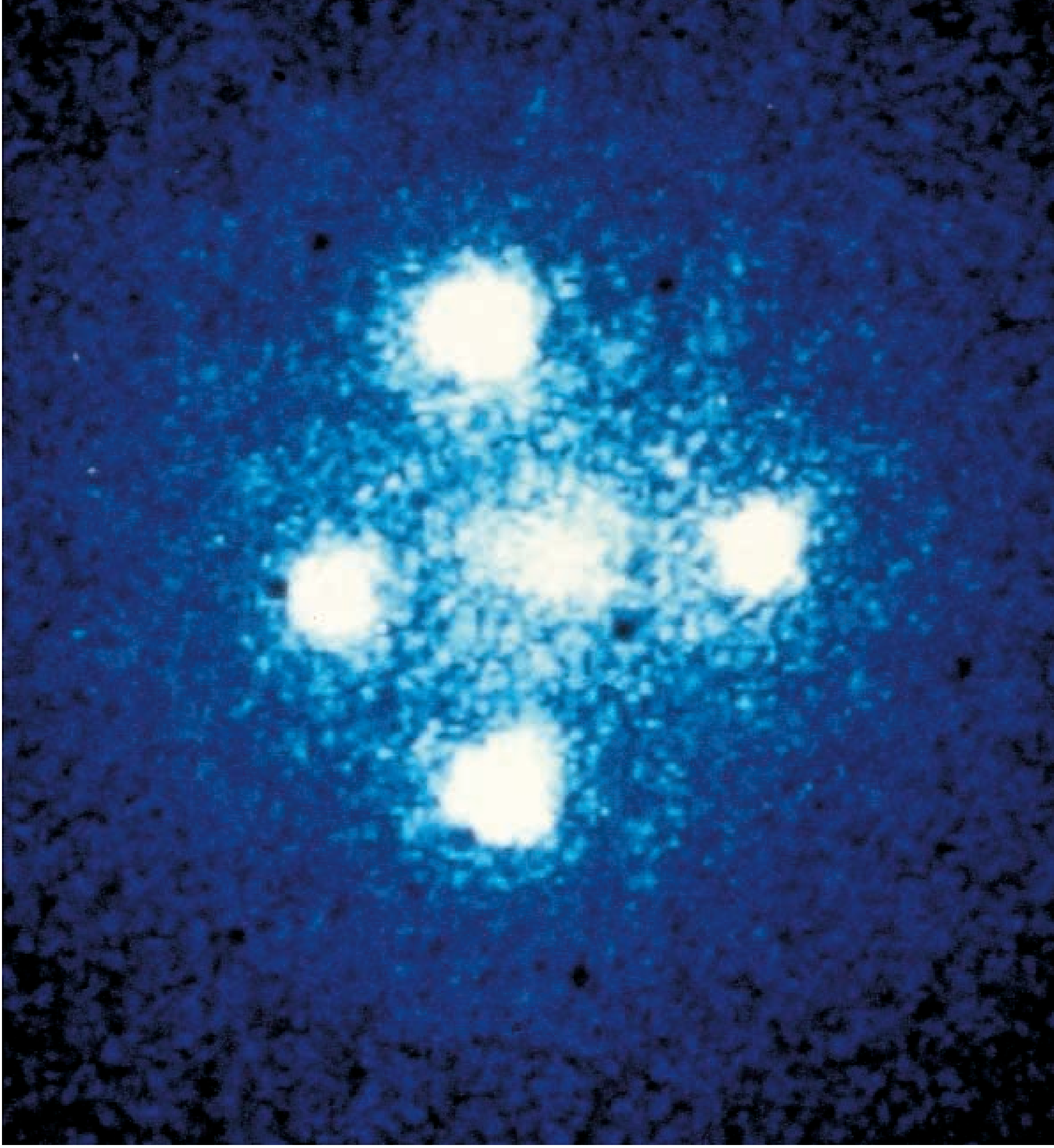
The unique ability of the astronomer to observe the past is not a free ride. The prize is that he cannot observe distant objects as they are today. Here theory jumps in. One *assumes* as a first step that one has observed a time series and then checks with more and more sophisticated computer models, always maintaining the universality of the laws of physics, whether the information from the young Universe does indeed lead to the present (nearby) Universe. With gigantic computers this process can be carried now to such detail that there is no doubt that the observed differences between "out there" and "here" are simply due to *evolution*.

If one looks into extremely large distances one will see no more galaxies because the look-back time brings the observer back into an epoch *before* structure formation when the stars had not yet lit up and the Universe was still dark. The observational proof of this distant cutoff of galaxies seems presently at hand.

There is, however, one still earlier source of radiation which can be observed today. It comes from a time, barely 500,000 years after the Big Bang, when the entire Universe was a single "primordial fireball" with a temperature of 3000 degrees. At this temperature the Universe became transparent for the first time, because the free electrons, which had made it opaque, could now take their places around the protons. Once the Universe was transparent, the glow of the primordial fireball could not vanish and it must still fill the present Universe. Yet the Universe has expanded since by a factor of about 1000 and the radiation's wavelength must have been stretched by the same factor such that – as *predicted* by G. Gamow in 1946 – it must now lie in the mm wavelength region. The actual observation of the so-called "Cosmic Microwave Background" (CMB) with a radio telescope by A. Penzias and R. Wilson in 1965 is considered as the definite proof for a once very hot and tiny Universe, and the discoverers were accordingly awarded the Nobel Prize.

The CMB radiation not only supports the Big Bang Universe, but also shows *minute* temperature variations from one place in the sky to another. These fluctuations are the very early seeds of the subsequent structure formation. The smallness of the fluctuations is the most dramatic demonstration of evolution in the Universe, because they reveal that the Universe at an age of 500,000 years was almost structureless and has since mysteriously evolved to ever higher complexity.

Although electromagnetic radiation cannot bring us information from still earlier epochs, there are other ways to investigate the young Universe. The primordial nucleo-synthesis 100 seconds after the Big Bang has already been mentioned. Theory supported by direct experiments at CERN, can describe the Universe back to an age of 10^{-10} seconds. Then one depends on certain observed boundary conditions and our knowledge becomes more and more speculative with every factor of 10 one goes back in time. At



an age of 10^{-42} seconds our understanding of physics breaks down, because General Relativity and Quantum Physics have to be applied simultaneously, which is still impossible. Even if this barrier will eventually be overcome there is no hope to ever describe the time zero. The Big Bang itself will always remain hypothetical.

Figure 11. The so-called Einstein Cross. It shows in the center a galaxy which acts as a gravitational lens. The four surrounding images come from *one* quasar in the background. As the quasar varies in luminosity the four images react at different times (!) because the light paths differ by some light-days (i.e. several 25,000 million km).

The Concept of Time

In daily life one has a rather unrealistic concept of time. Time is considered as connecting the past eternity with the future eternity in uniform steps. In reality time began at zero in the Big Bang. There was no time *before* the Big Bang, and the question what was before the Big Bang has for the physicist no meaning. Whether, on the other hand, time will lead into a future eternity depends on whether the cosmic expansion will eventually be halted, in which case the Universe will collapse under its own gravity into the "Big Crunch" and this would also be the end of time, or whether it will expand forever. Astronomers believe there is not enough matter in the Universe (including the above-mentioned Dark Matter) to ever halt the expansion. This believe was strengthened in 1998 when rather strong evidence was found for a fifth force in the Universe (Einstein's so-called "Cosmological Constant") which drives the Universe into an accelerated expansion. It would correspond in the yeast cake to an *increasing* power of the yeast. Therefore the view is favored that the Universe will expand forever and time will never come to an end. It is, however, imprudent to extrapolate our limited knowledge into eternity, and one should say more carefully that the Universe is likely to expand into a very distant future.

In addition time is uniform only for an observer who travels with constant speed through space. Any acceleration will change his clock rate. Consequently there are hardly any two observers in the Cosmos who have the same clock rate. In our technical age this relativistic effect has already *practical* consequences. Clocks on satellites orbiting the Earth run slightly differently than on the ground. If this difference was not accounted for communication with these satellites would soon be lost. This leads also to the famous "twin paradox-on" which requires that a twin travelling fast through space will return younger than his brother left on the ground.

The variability of the clock rates implies immediately that the idea of simultaneity is a misconcept. A stunning example is the Einstein Cross **(Figure 11)**, where the gravity field of a foreground galaxy bends the light rays of a distant quasar (i. e. a particularly luminous galaxy) such that the same quasar is seen four times! Quasars have variable luminosities and the four images vary accordingly in brightness. However, the four light paths differ somewhat in length, and as a consequence a given luminosity outbreak of the quasar is observed in the four images at *different* times! If the Einstein Cross was a prominent object in the sky this would have been noticed long ago and the concept of simultaneity would never have been born.

In addition to the Einstein Cross many other gravitational lenses are known today **(Figure 12)**. They all are impressive demonstrations of Einstein's prediction that light rays are deflected by gravity. Therefore light propagates through space along curved lines. But since nothing is more straight than a light ray, our believe in the existence of straight lines is also a misconcept.

In principle the entire space could be positively curved, flat, or negatively curved. Even if space is flat, as presently believed, the existence of structures and the accompanying variations of the gravity field, force every light ray on a curved path.

Figure 12. All the blue images in the picture come from the same galaxy or from parts of it. In about half the galaxy's distance is a large cluster of galaxies whose tremendous gravitational field bends the light and causes the multiple, distorted images of the background galaxy. (Picture taken with the Hubble Space Telescope).

Epilogue

The few examples from the field of astronomy show that our thinking is fundamentally influenced by science. Nature is infinitely more complex than conceived in daily life. The human mind tends to extrapolate daily experiences into natural laws which have nothing to do with reality. Apparent facts like the absoluteness of time or the existence of straight lines are erroneous. On the other hand speculations about a single creation event and subsequent evolution are factual.

It is here the place still to counter another misconcept. We have today not much difficulty to accept the fact of evolution. But we make easily the mistake to assume that the present World and present man are the end product of evolution. In reality evolution must continue. In 100,000 years we will not recognise our descendants, and in say 50 Gigayears the last star will extinguish and thus terminate all possibility for life. Organic life, which we value so highly, is nothing but an intermezzo in the evolution of the Universe.

The author

Gustav Andreas Tammann, born in Göttingen on the 13th of June in 1932, spent his early years in Basle, where he attended the schools and then registered at the University of Basle in astronomy. Indeed, this proved to be a wise decision. On one hand, the old humanist tradition of this University provided G.A.Tammann with essential cultural ingredients. On the other, it was the key to a field of science which was due to bring forth many spectacular discoveries in the years to come. Further study years saw him in Freiburg i. Br., Göttingen and Basle again, where, in 1961, he acquired the Dr. phil degree.

In 1963, the great American astronomer Professor Allan Sundage offered G.A.Tammann the opportunity to join his research team in the frame of a post-doctoral employment in Pasadena (USA) introducing him into the research of the extragalactic Universe. The focus of research was on the determination of extragalactic distances and the expansion of the Universe. This subject, and the still lasting friendship with Allan Sandage, are among the most important cornerstones of his stay in Pasadena. In 1972, he returned to Europe and was appointed Professor of Astronomy in Hamburg and in 1977 in Basle, where he became Director of the Astronomical Institute. In these years, G. A. Tammann began with furthering scientific activities in Switzerland. Among many other honours, he was elected scientific representative in the European Space Agency's Science Programme Committee and Chairman of the Swiss Committee of Space Research. In both functions, he followed Professor Johannes Geiss. When it came to decide on the Swiss membership to the European Southern Observatory, it was up to J. Geiss and G. A. Tammann to develop the necessary lobbying activities.

G.A.Tammann is not only a wonderful teacher, but also an outstanding communicator to the public at large. In countless interviews on radio and television but also in many articles, he reported on the findings of modern astronomy.

A curriculum of G. A. Tammann would not be complete if one would not briefly mention his interests outside the boundaries of natural sciences: music, history and art. Classical humanistic tradition and the paradigms of modern scientific research have been the grounds allowing G. A. Tammann to grow to one of this country's best-known scientists.