Can We Understand the Cosmic Evolution?

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I want to thank you to be allowed to speak in these philosophical circles, though my knowledge of philosophy is rather sporadic. And in effect I want to do something, which Wittgenstein actually scorned at. He once wrote that the scientists want to make us believe that they can explain the world. What the word 'explain' means is not so obvious especially if I take another quotation of Wittgenstein, according to which the meaning of a word is given by its use. But 'explain' is used in so many ways that it practically means everything, therefore nothing.

I will try to present some facts from contemporary physical cosmology. But nevertheless let me start with something philosophical, with the credo of existentialist philosophy: namely, that we are thrown into this world without our consent and without assistance. Now there is no question of denying that credo, but then it continues "we are left so alone in this world". Here I would start to disagree a little bit, because in contradistinction to other creatures we have a precious gift, our intelligence. How this came about, is not really understood because it seems that our neural equipment has been already in place about a hundred thousand years ago, although at that time the ability to think abstractly was not really a selectional advantage. It is just now, in the last hundreds of years, that we learn to read the book of nature, which is written in the language of mathematics—as Galileo already noticed. And in the last fifty years or so this knowledge enabled us to develop all this high technology, by which we really became the masters, at least, of our solar system.

And today, we can even ask the question about the whole universe. Who ultimately dictates what is happening here? I will first illustrate that this is a combination of chance and necessity. We see that what happens in nature is regulated by some laws, but they do not determine everything uniquely. There is an irreducible element of chance involved. Both chance and necessity together conspired in such a way that ever more complex systems were created until finally man has evolved. This is a very long history, and to appreciate it, one has to see the whole panorama of the cosmic evolution. Due to lack of space, however, I can only give three snap-shots of that panorama,

F. Stadler, M. Stöltzner (eds.), *Time and History. Zeit und Geschichte*.

which are taken more or less arbitrarily. In a recent book, I have outlined some additional features, but also this is by no means exhaustive.[1] In fact there are books that are twice as thick, and they are not exhaustive either. But taking them all together, one obtains a great number of facts that show how elements of chance and of necessity conspired in such a way that human life could emerge. It is a sort of miracle that we can sit here together. At the end of my paper, I will discuss various views how one can understand this miracle and what is a good way to look at it.

I.

The first topic I have chosen is the Big Bang. Now, do not ask me what was before the beginning. I think at the beginning there was no beginning. But I will say what happens, say, a couple of minutes after the Big Bang. Then we are on fairly solid ground and can understand what has happened. The Big Bang is today the favoured theory of the universe, and I think there are pretty good reasons to believe so, at least as regards the principal ideas. It rests on three pillars which are quite independent of each other, and they are fairly convincing. One is the cosmic expansion: one sees the stars and the galaxies as the products of a big explosion; they all go away and the further they are away, the faster they go. This is precisely what you would expect after a big explosion. And the second pillar is that from this big explosion one still sees a little bit of light, the first lightening or, if you wish: "There be light". This light has somewhat deteriorated, but with the modern methods it can still be found and measured quite accurately. Within a tenth of a per mil it agrees with what you would expect to obtain from a hot body. And, thirdly, the distribution of elements agrees very much with this picture. At the beginning, certainly, there were only the most primitive elements. The most primitive one is normal hydrogen, which consists of a single proton. Of course these protons could take part in some nuclear reactions, but the available time was extremely short because everything was diverging so fast, and the best they could do at that time was to form helium out of four of these protons. To go further in the periodic table is rather difficult because to get beyond helium would require that you first go to beryllium-8, which are two helium nuclei. But they do not stick together, hence you need to go

1 Walter Thirring: *Kosmische Impressionen. Gottes Spuren in den Naturgesetzen*, Wien: Molden (2004).

on to carbon-12, which means three helium nuclei, but these three nuclei have to be very close together, which is rather improbable. Such processes, of course, happen inside the stars where one has billions of years time, but not at the moment of the Big Bang. So the Big Bang theory predicts that there is mainly hydrogen, a little bit of helium and perhaps a tiny little bit of heavier nuclei, but that is all there is. And this agrees very well with the distribution one finds in the cosmos, where about three quarters of the matter is in the form of hydrogen and one quarter is helium, and the rest is very small. So as carbon-based creatures we are rather exceptional, after all, we are part of the atomic waste that is subsequently bred in the nuclear reactors inside the stars. I will come back to this below.

The picture just outlined is fairly well established, although it took a long time until it was accepted. Originally it was another theory, the so-called steady-state theory, to which the majority of the scientists tended. It was, in effect, an atheistic prejudice which led people to think that the Big Bang theory was not satisfactory because it resembled an act of creation, a miracle or a breaking of the laws of physics by generating all this universe out of nothing, a *creatio ex nihilo*. People preferred the steady-state theory instead, where the universe was eternal. It had always existed, and this appeared philosophically neutral. So there were some philosophical prejudices. But eventually, it turned out that, in actual fact, the universe had a definite beginning, so that cosmologists had to cope with the question how that could have happened. Luckily it turned out that this specific *creatio ex nihilo* is not such a problem for science. In fact, it can be accommodated to the laws of nature. In this case the relevant laws are Einstein's theory of gravitation, his general theory of relativity. The two big questions are: First, there is this tremendous energy in the universe, how could this be created in a way that is compatible with the law of energy conservation? Second, how did it explode in the first place? This is rather counter-intuitive because gravitation is attractive and it rather tends to implode things.

At first these questions seemed not to be answerable, but it turned out that in Einstein's theory they can be easily accommodated (let me use this word 'accommodated' rather than 'explained' or 'deduced'). In particular, the problem of the energy conservation disappeared almost by itself. While the matter has such a large positive energy, gravity has a negative potential energy. One can see how much from the laws of celestial mechanics. In fact there the potential energy, as the virial theorem tells us, is negative and twice as big as the kinetic energy. This theorem has a generalization in general relativity, which says that a closed universe is very light, in fact it weighs nothing, it has zero energy. The negative gravitational energy exactly compensates the energy present in matter. So the *creatio ex nihilo* does not cost any energy, and you do not have to become indebted in energy to make it possible. The *creatio* may be inhibited by other factors, but energy conservation is not an obstacle. So this first objection against the Big Bang theory has gone away.

Now, what about the explosion and the implosive nature of gravity. It turns out that this is not necessarily so in Einstein's theory of gravitation. For, the source of gravitation is not only the energy, but the energy plus three times the pressure. Usually the pressure is very small compared to the energy, so one can forget about it. But it may be that this pressure is of the same magnitude as the energy, which would be the case for a radiation gas. And it could be even negative. Now this sounds a little bit funny; what means a negative pressure? Many scientists worried about that, and also Schrödinger, who called it an "innerer Zug", thought that it did not really make sense. But, at closer inspection, one sees that it is not so obviously non-sensical because what one feels are only pressure differences, and the absolute value of the pressure does not manifest itself, except for Einstein's theory. And there it is a source of gravitation and, if it is negative, it is, in effect, a source of anti-gravity. This change of signs tends to make gravitation repulsive rather than attractive. It may even be that the pressure is more negative then the energy is positive, and then we have an anti-gravitating situation. In fact, it was Einstein himself who invented such a source of anti-gravity by introducing his famous cosmological constant. To be sure, he wanted to use it for quite another purpose. He believed that the universe was eternal and fixed forever as an everlasting background of all the processes in nature. He also studied a cylindrical model of the universe; however gravity tended to implode it. Therefore he added a so-called cosmological term such that the resulting anti-gravity would balance the gravity and there would just be a static universe. Now doing so did not really make his universe stable because if you added a little bit too much of anti-gravity, it would explode and if you added a little bit too little, then it would implode. This was too delicate a situation to be acceptable for cosmologists.

But then people found this cosmic expansion, and the Russian mathematician Friedmann showed that from Einstein's equation without this cosmological constant, you really obtained a nice model of the universe.

However this expansion had to be put in from the very beginning. So Einstein abandoned his cosmological constant and considered it the greatest blunder he had made in his entire scientific life. Yet, he did not completely abandon it. When I was in Princeton in the year 1953/54 I met Einstein. During this year he only once came to a physics colloquium, and this was a report on the cosmic expansion. He was very alert and he wanted to know, whether this cosmic expansion speeds up or whether it slows down. If you had gravity, of course, it would slow it down, but if you had this cosmological constant, it would speed it up. And apparently he still thought that maybe there was something interesting in the cosmological constant. Of course, at that time the data were so inaccurate that this question could not be answered. But today we can answer it and, curiously enough, the answer is that the anti-gravity dominates. The expansion of the universe seems to speed up. So there is this anti-gravitating matter around; or rather, it is not matter but dark energy, and what that is, today nobody knows. And in fact you would not expect to see a lump of anti-gravity matter, because anti-gravity is repulsive. It would disperse very finely all over the universe. This apparently is what it is doing now, and it seems what it has done to an even larger extent at the beginning of the universe. At this time the anti-gravitating stuff was rather dominant and brought about an inflationary explosion of the universe. For this reason, today's cosmologists talk about an inflationary phase in the evolution of the universe.

In the Friedmann universe you had to put the expansion in by hand by choosing the appropriate initial conditions. This simply says that it just happened that initially the universe was very explosive and that we see today the product of that explosion. But such an ad hoc explanation is not very satisfactory, even less when applied to the whole universe. It is somewhat like launching a satellite. If you shoot up a satellite and if you do not have sufficient thrust in the beginning, it will fall down again; and if you give it too much thrust it will go away forever. To keep it on a stationary orbit, you have to be very precise. It took humanity quite some time to work that out. Roughly speaking, the same occurs with the Friedmann universe. If you give it too much speed at the beginning, then it will spread out too quickly and there will be no formation of galaxies or stars. And if you give it too little speed in the beginning, then it will re-collapse again. Hence, in order to arrive at the present situation, you have to be quite precise at the beginning. And in fact, 'quite precise' is an understatement. You have to be exceedingly precise, because the natural time for such a universe is given by the gravitational constant and the other fundamental constants of nature, the speed of light and Planck's quantum of action. This yields a time, the so-called Planck time, which is incredibly short. It is 10^{-43} seconds. To arrive at the present universe, which is about 10 billion years old, you need a very precise initial thrust.

All this sounded a little bit phoney and ad hoc. But when the inflationary theory was invented, you suddenly had a mechanism that yields the required expansion and longevity. Thus you might wonder, whether you can explain the present situation just by these new basic laws and do not need any fine-tuning. Unfortunately, this is not so. You still need a benign accidental happening that occurred just at the right time. At the beginning, the explosion was like a real explosion. It would grow exponentially and if you let this go on for a long time the universe would have been thinning out far too much. You have to break this strongly explosive phase at the right moment. According to our present picture, this happens by a change of the fundamental state. It is like in radioactive decay where you go from one state to the other. In the mean you can say how long it will last, but how long it lasts in an actual situation is not prescribed by quantum mechanics. If you have a single nucleus of uranium, then its average lifetime is about 10 billion years, but nobody can predict when it decays, whether right in the next moment or somewhen between now and 10 billion years in the future. And similarly, when this inflationary phase exactly stops, so that we have a universe full of life after 10 billion years, is not really determined by the theory. However, we crucially need these 10 billion years for the biological evolution. In fact, as we will see, there are three or even more time scales all of which accidentally have to lie in this 10 billion years range, so that evolution can work. This is how necessity and chance come into play here. That is all I wanted to say about the beginning and so let me make a big jump. How the elementary particles were formed and what their properties are, is also a very exciting subject, but I have to pass this over and come to another important issue, in a certain way to 'astrology', if you wish: Namely, what is the secret of the stars?

II.

Of course, the astrologists have no idea about what is the secret of the stars, and it may even be surprising that there is any secret at all. For, the stars are the most primitive objects in the universe. There is no life, there is no chemistry, and there are not even atoms. Stellar matter is just a uniform soup of a gas of electrons that is uniformly spread out and the nuclei are floating inside this gas at basically random positions. It is what physicists call a jellium. It has no further structure, and is completely characterized by two numbers only, the density and the temperature. To give an example, in the middle of the Sun, which we now know pretty well because with our neutrino eyes we can see through the outer layers, the temperature is 15 million degrees Kelvin and the density is 150 times that of water, which is pretty high for hydrogen. It is more than ten times that of a heavy metal, so much it is compressed. That is all we can say and all we need to know about it. So how can there be a secret? Nevertheless, there is a very refined mechanism, which makes the whole thing work, such that the Earth can support life.

Let me, for the time being, play the part of a cosmic architect, who wants to create a structure that can support carbon-based life. Now what we need for life is, first of all, the sunshine or, roughly speaking, temperature differences because we want to create ordered structures. These are contrary to the second law of thermodynamics that tells us that things become more chaotic, that temperature differences are levelled out, or that the entropy is always increasing. This seems to be the law. But we live of the sunlight, because the sunlight is a diet that is rich in energy and lean in entropy. Thus we can very well become a little bit more ordered or make our entropy a little bit lower at the expense of increasing the entropy of the sunshine, whose entropy is anyway too low. So we can increase the overall entropy whilst becoming ourselves a little bit more ordered. If you want numbers, the entropy of the sunshine is essentially the number of photons. The photons arrive on the Earth with the thermal energy they have on the surface of the Sun, where the temperature is 6,000 degrees, and we break this energy up into photons, which have a thermal energy corresponding to the temperature on the Earth, which is 300 degrees. So we break one photon into 20 photons and thereby we increase the entropy of sunshine by a factor of 20. Hence we can save a little bit of entropy and decrease our entropy a little bit without increasing the overall entropy. All this can be followed mathematically and from the saved entropy you can create, say, per year a forest which is forty metres high or so. This is the order of magnitude of how much order you can create from the sunshine. In fact these are only rough numbers. I wrote these estimates in my book and sent them to a colleague of mine in California. He wrote me he had redone the calculation and obtained sixty meters.

I could only answer him: Well this is probably so because in California you enjoy better summers than we do over here.

But how can one get the indispensable sunshine? First of all the problem is, of course, how to get out of thermal equilibrium. Boltzmann's famous picture of the heat death amounts precisely to the question, why the universe has not reached equilibrium by now. The problem at issue here is far more severe because we want to know, how the universe did get out of the equilibrium in the first place. For, nowadays we know from the cosmic background radiation that initially the universe was in a very good equilibrium. The deviations from the equilibrium distribution are only about one tenth of a per mil, so this is almost nothing. It is a perfect equilibrium. Apparently the universe got out of equilibrium by a kind of condensation. As the universe expanded, things were condensing by gravity, and the stars were formed like drops in condensation phenomena. So far this is not so surprising. But condensation alone is not enough, because when you condense, say, the water drops in a cloud chamber, after expansion, they are not hotter than the rest, they have the same temperature. Therefore you want a special kind of condensation phenomenon, where things, when they condense, become hotter than the rest. And now gravity indeed furnishes this peculiar kind of phase transition, which is accompanied by an effect that is essential for the life of the stars; to wit, it has, technically speaking, a negative specific heat. This means in ordinary language that the system tries to shrink and when it shrinks it is getting hotter and then it gives off energy, and as it gives off energy, it shrinks even further and gets even hotter. So upon giving energy off, it becomes hotter. And this is just the opposite of what we are used to: when something gives off energy, it becomes colder. So the first thing to do as a cosmic architect is to invent this special kind of phase transition, which is contrary to the rules of classical statistical mechanics. There the specific heat is always positive. In many mythologies the Sun is deified in the sense that it becomes a god, like the god Ra of the old Egyptians. A god has to identify himself by doing miracles, and in some way the Sun does right this by achieving something that contradicts the laws of classical thermodynamics.

But a negative specific heat is still not enough because we want this temperature difference to persist for a billion of years, that is, for the whole time of the biological evolution. However, the first difficulty arises to achieve this with the energy from gravity alone. Lord Kelvin was able to show that by some simple calculation. Actually he made this calculation exclusively for the Earth and could at that time not say whether the Earth's energy balance with respect to the Sun was positive or negative. In my book, I have a better calculation.[2] At any rate, the order of magnitude is correct, the sunshine carries away the gravitational energy of the Sun in a couple of million years. And we know that this is far too short for biological evolution. A couple of million years was just enough to form man from hominids, but not enough for the prokaryotes to form higher biological systems. So I have to invent another source of energy, which is about thousand times as powerful. And this is in fact furnished by nuclear energy. It was one of the major break-throughs in the history of our physical world-view, when the Viennese physicist Fritz Houtermans found in 1929 that solar energy is nuclear energy, although at that time nuclear physics was almost non-existent. And this great insight came about, because George Gamow had found something that, once again, contradicts classical statistical mechanics. According to the latter, nuclei at the temperature prevailing in the middle of the stars, i.e., 15 million degrees, never can come close enough together because their Coulomb repulsion is so strong that it is against energy conservation that they can meet and react. Gamow found that quantum mechanics makes this miracle happen, nevertheless, by what is called the tunnel effect. Nuclei can tunnel through the Coulomb energy barrier and react. Although these miracles are very rare, they happen occasionally and nuclear reactions take place. And we want these nuclear reactions to extend over a very long time of the order of ten billion years. Actually the energy output per time is very low, even though the nuclear reactions are so powerful. It is much less than in an ordinary stove. You can easily calculate that, because the energy of one nuclear reaction per atom is about of the order of a couple of MeV. But if you spread it out over a billion years, it is per year about a thousandth of an electronvolt (eV). In contradistinction the chemical reactions in a stove are, after all, of the order of one eV per particle. Solar energy is thus about a thousand times less active than a stove heated once per year.

So it seems that the cosmic architect can handle the problem of maintaining the temperature differences with the help of nuclear energy and quantum mechanics. But not quite so, because the question is how can one reach stability. We know that nuclear reactions are explosive. Thermonuclear reactions happen in fact very rapidly because once energy is created, it increases the temperature and, as you increase the temperature, you increase

2 Thirring, op.cit., 202–204.

the energy output. This is something that is exponentially enhancing itself, and therefore it becomes very explosive. So why did the nuclear material in the stars not generate an explosion? Now it turns out that this instability is just tamed by the other instability I was talking about, by the thermal instability. The thermal instability tells you that the thing does not try to explode but to implode, and then it becomes hotter and as it becomes hotter it emits more energy and becomes even hotter. So you have an explosive tendency from the nuclear reactions and implosive reactions from this negative specific heat, and these two instabilities work in opposite directions. Thus they just cancel each other exactly and that leads to a stable situation.

You can now picture the secret of the stars as follows: There are two giants inside the star and they tend to destroy it, but in opposite ways. So they lean onto each other and mutually support each other in an exceedingly stable way, which lasts for billions of years—just the time we needed for our biological evolution. But the catastrophe happens if one of the giants gives in. Then the whole safety system collapses. Both of these possible disasters actually occur in stars. The first occurs, when the negative specific heat gives in. This happens once the star has imploded so much that the electron gas becomes too dense and too degenerate. It turns out that for a degenerate electron gas, this mechanism of negative specific heat does not work any longer. In this case the nuclear material explodes, and we obtain what is called the 'helium flash'. This happens when all hydrogen has been already burned out and when the stage is reached, where also helium can burn. It does so explosively, but only in the middle of the star. The rest outside is not yet so dense and still has the negative specific heat. It can absorb that energy and it becomes a little cooler, paradoxically, in doing so. But this is not a real trouble, it just looks a little bit as if the star has some digestion problems inside; you do not see a catastrophe.

The real catastrophe only happens in the second case, when the nuclear energy gives in. Now, this happens at the moment when the energy generated by shrinking the star by gravitation, can be transported out too quickly. If it is just by the photons, which are created by nuclear fusion, this transport is too slow. If they were able to go out directly, they would do so in a few seconds and transport out the energy immediately. It actually takes millions of years until a photon gets out from the centre of the Sun, just because it is scattered so often. So that is a very slow process. However, when too much energy is there in the centre, a new process sets in, where the electrons creep into the protons and they create a neutron and a neutrino. The neutrino has the property that it hardly reacts with any matter at all; it can escape directly. And so it escapes immediately and carries off the energy and then, since also the electrons have disappeared, which carried the weight of the star, the star collapses within a few seconds. This makes the huge cosmic catastrophe of a supernova, where a star within seconds attains a luminosity that is about a billion times bigger than the luminosity it originally had. Then it becomes as bright as its whole galaxy; so this is a really terrific happening. And what happens then is either that there remains a neutron star or we obtain a black hole, which is a very strange object. Be this as it may, we owe our lives to this explosion since, after all, in this way the stuff we are made of, carbon, oxygen and nitrogen, finally gets into space. I cannot go into further details, but we see again, that things have to be very fine-tuned so that we eventually have a physical basis for our life. To sum up, the stars, which for a long time seemed to be the model of eternal fixed points, are in fact very unstable But they are stabilized by a very delicate mechanism, which is able to stabilize them for an incredibly long time. Much more stabilized, one might add, than we can stabilize our nuclear explosives. In our nuclear reactors, safety rests on the assumptions that human error does not happen; but error is always possible. Stellar stability rests on the assumption that the laws of nature do not make any error, and therefore we have a stability of billions of years.

III.

Let me now come to the third topic I want to discuss, the stability of our planetary system. It is in a certain sense a very amusing part of the history of science. The problem appeared because of the ability to make very good observations already in ancient times. People could distinguish between the fixed stars, which rotate rigidly on the night sky, and the planets which seem to sneak through all that, some very ostensively like Venus. She sometimes appears in the morning, sometimes in the evening. Already in the Middle Ages people worried, why there is no danger of collision. In some way somebody has to control the heavenly traffic. But who was there? People said there could only be angels to do the job. The angels, they thought, are rather unemployed; they have nothing better to do for the time being, so let us use them as a cosmic traffic police. Therefore they imagined that the motion of the planets is guided by the angels. And Newton thought that sometimes even God has to intervene and bring all this planetary system into order, otherwise it is leading to chaos. This shows that Newton, although he had no idea about the time scales involved, had a really superb vision to see that there was a problem. But then people got acquainted with Newton's equations of motion and they thought there was no room for external interference. Laplace had just figured out that even the resonance between the orbits of Jupiter and Saturn was not a catastrophe, even though it was almost equal to 5/2. So this clockwork seemed to be working perfectly. And when Napoleon asked him: "Where is God in your system?", Laplace famously responded: "Sire, I do not need this hypothesis". But Laplace had somewhat underestimated the difficulty of establishing the stability of the planetary system, so that people kept on calculating and giving proofs of its stability. Then others showed in turn that there was still a gap in these proofs. This went on for a long time until King Oscar II of Sweden got fed up with this fooling around and wanted the matter to be settled once and for all before his sixtieth birthday in 1889. He offered a lot of money as the prize for the man who could show from the basic equations of celestial mechanics that the planetary system was stable. This excited the most powerful mathematicians of the time, they submitted their contributions, and the jury finally awarded the prize to Henri Poincaré. And the Swedes founded a special journal for mathematics, the "Acta mathematica" that still exists today, and wanted to publish Poincaré's winning essay in the first issue. But then the catastrophe struck: Poincaré found that in his proof there was still a weak point, that it was not a proof. And so honestly he wanted to withdraw his paper. But it was too late, the first issue of the "Acta mathematica" was already printed. All copies had to be destroyed and replaced by another first issue, which costed Poincaré more than he had obtained for the prize. But Poincaré's ideas were later published in a separate book titled *New Methods in Celestial Mechanics*. These methods are still the basis of today's thinking about the subject; so finally Poincaré also had some income.[3] But still there was no proof of the stability of the planetary system.

Then in 1909s, a Swedish mathematician, Sundman, could prove what Poincaré had wanted to prove, but only for a very special case, namely where you had only three bodies. He proved the stability in the sense that the equations of motion tell you what is going to happen with three bodies up to infinite time. Yet he was cheating a little bit. When two bodies collided,

3 Henri Poincaré: *Les Méthodes nouvelles de la mécanique céleste*, 3 volumes, Paris: Gauthier-Villars (1892, 1893, 1899).

he had to introduce another time scale, which resolved this ever faster motion. But if you granted that, it was a rigorous mathematical proof. As a matter of fact, introducing different time scales when things are getting too close to one another is what everybody has to do on the computer today. So let us accept that Sundman proved the stability of the three-body system. But then it turned out, if you proceed to four bodies, this does not hold any longer. Two American mathematicians, John Mather and Brian Mc Gehee, constructed a counterexample that consists of a pair of bodies, one single object, and a sort of messenger body between them whose motion becomes faster and faster. So for a special orbit after a finite time the forth body is kicked to infinity.[4] And once you are at infinity, you do not know what to do anymore, so you cannot continue the evolution to infinite times. Now, this was again a case that involved two colliding objects. Hence, people were sceptical about the general value of that example. But in 1992 the Chinese mathematician Zhihong Xia [5]showed that if you have five bodies, you do not even need a collision. You need only ever closer encounters and the same thing happens: you reach infinity in a finite time. So eventually the definite answer to the question of Oscar II is negative, there is no stability in the intended sense. But then you might wonder whether in physics we really have to worry too much about these funny orbits; they are something very isolated.

So let us ask other, more specific questions about our solar system. Is this particular situation stable? And let us not ask questions about eternity; these are silly questions. We are satisfied if our climate is stable for some billion years. And then the modest first question to be asked is: Can the situation be so chaotic that a little change in the initial conditions makes, after a certain time, a difference that endangers our climate. After such a long time, however, this kind of statement becomes pretty meaningless because the present state cannot be determined within the required accuracy. Determining the position of the Earth within a fraction of a millimetre obviously does not make any sense. So what you really want to ask for, is the so-called Lyapunov time, the time after which the sensitivity of initial conditions becomes too large. A decade ago this time was estimated by the

4 John Mather and Richard McGehee: "Solutions of the collinear four-body problem which become unbounded in finite time." In: *Dynamical Systems Theory and Applications,* edited by Jürgen Moser, New-York: Springer (1975), 573–587.

5 Zhihong Xia: "The existence of noncollision singularities in newtonian systems", *Annals of Mathematics* 135 (1992), 411–468.

French mathematician Jacques Laskar.[6] He found that the Lyapunov time is very long on our scale, about ten million years, but not long enough for the cosmic evolution. So the predictability was given for ten million years, but not for the billion years we need. Recently this result was challenged by the American mathematician William Newman who had a more powerful computer. I should say the result of Laskar was partly analytical but partly it was computer-aided. And the American mathematician now claims that this time which Laskar found is actually not a Lyapunov time of the solar system, it is the Lyapunov time of his computer. Any computer, by rounding off errors, mixes in some uncertainty into the game. And he claims he has a better computer and he has increased this Lyapunov time to almost a billion years. Now I have no way of controlling this statement, it still is not long enough but it is remarkable.

In the end you might want to forget about all these computer freaks; we will never be able to compete with them, so let us ask a more simple but relevant question. Namely, if we do not take the present solar system as it is, but fiddle a little bit around with its parameters. We change the masses of Jupiter and other planets, we change their positions, and we ask under which conditions can we have a stable situation for a sufficiently long time. What means a stable situation? What stability do we want? We do not care whether the equations determine things up to eternity. We want to know whether for a couple of billion years we have a reasonably stable climate. Whether the eccentricity changes only a little bit, whether it changes too much, or whether eventually we will even be kicked out of the solar system. Now if you play a little bit around with this, you find for most parameters instability in the sense that the eccentricity becomes too big or that we are even kicked out of the solar system. This can very easily happen after a comparatively short time, about hundred or thousand Jupiter years, it does not take very long. That things are so stable, we owe to many accidents, namely that Jupiter is at a good distance from the Sun. If it would occupy, say, the orbit of Venus, we would have no chance. Another accident is that Jupiter is heavy, but not too heavy. If it were as heavy as the planets in the newly discovered planetary systems (they are much heavier than Jupiter), there would be no possibility of stability either. Clearly the planetary orbits have to be well separated. If they overlap, then eventually it comes to a close

6 Jacques Laskar: "A numerical experiment on the chaotic behaviour of the solar system", *Nature* 338, 237 (1989), and "Large scale chaos in the solar system", *Astron. Astrophys.* 287, L9 (1994).

encounter and disaster is looming. So our situation is indeed very special, I would say.

Of course you can advocate a sort of Darwinist explanation and say: Maybe at the beginning there were plenty of planets and everything that was not stable has already been kicked out of the solar system. These former planets collided, as some apparently did breaking up into the asteroids, or maybe they were thrown into the Sun. So what we see now is something where all these irregular things had been weeded out and what is left is really stable for such a long time. So we arrived at another picture of our planetary system. It used to be the clockwork par excellence, where everything is determined. And now, on the larger time scale, it looks more like a biological system, a product of an evolution, where finally something good has come out. What the probability is that you can use this selection argument and eventually arrive at something useful, is a question that has not been answered yet. At any rate, we see that in the case of stability, once again, chance and necessity come together to make our lucky situation possible.

IV.

So let me finally comment on the various general views you can entertain about the extraordinary fact that the universe evolved in such a way that highly organized systems could form. An admittedly coarse classification distinguishes an atheistic view and a theistic view. Perhaps I should rather speak about an agnostic view because I do not really know what are the dogmas of atheism. This view holds that it all happened just by accident, in German "Zufall", or with Monod, "hasard".[7] Despite all this linguistics, this view simply says: "It is just an accident that it happened this way." And the theistic view is that all this is guided by the Almighty in such a way that man can exist.

Let me first comment on the accident or the "Zufall". I must frankly admit that I do not exactly know what it is. But what I know is a probabilistic interpretation of it. The laws of physics give us probabilities. And at the beginning we only had the simplest situation, namely, a uniform probability distribution corresponding to infinite temperature. Then the probability is the ratio between the number of favourable cases to the total number of

7 Jacques Monod: *Le hasard et la nécessité. Essai sur la philosophie naturelle de la biologie moderne*, Paris, Le Seuil (1970).

cases. And in fact, if we have the Big Bang, then the original universe was in a state of high temperature, which is physically characterized by the fact that all states are equally probable up to a certain maximum energy. And then what are the numbers? Well, in a closed system this number is always finite, it is the exponential of the entropy S of the system. In physics it is the exponential of the number e, but you might as well take the number 10 if this is more familiar to you, it does not make any essential difference. So the number of cases is 10^S. And the number of the favourable cases? I am of course not interested in a particular situation, but only in a somewhat more ordered situation. And let us take the "more" in a very modest way, say it is more only by a per mil or so, the entropy is just decreased by a per mil. Then I get a very simple expression for the entropy and also for the probability. The probability, according to Boltzmann it is called W, is equal to $10^{S(1-1/1{,}000)-S}$. The number of favourable cases is the entropy slightly modified, slightly decreased, say by a factor 1 over 1,000. The number of favourable cases thus obtained is divided by the total number of cases, which is 10^S. Now if you look at that, you see, S in fact cancels out, and what remains is 10 to a power which is of course negative, it is a probability less than unity: It is entropy divided by 1,000. You see 1,000 and might think, well this is perhaps not so bad. But the trouble is that the entropy of the universe is huge. In fact, although it is finite, it is essentially the number of particles in the universe, which is 10^{80}. Dividing this by 1,000 yields a probability, which is practically nothing. It is so tiny that we can forget about it.

But nevertheless, people say they can explain the evolution scientifically or naturally. How do they achieve this? Do they cheat with the probabilities, or do they cheat with the evolution equations. Actually, they do both and they do it in the following way. First of all with the probabilities, and there is some reasonableness to that. When I say cheat, this may be a harsh word; you may use a kinder word. So you say, this is a different point of view or a different paradigm or whatever you call it. You forget about all this cosmos and the history and look only at the situation right here. Given all that, what is the probability that the biological evolution we know of happens? And let us not worry about the whole cosmos; let us look at a very small fraction of it, let us say a DNA. So the question is, how can a DNA come about just by accident. And then you say: Well it may not happen here, it may happen somewhere in the world. We know how many stars there are, they are so many, namely 10^{22}, and maybe somewhere this may happen by accident.

So let us look at the DNA. This is a structure made out of four bases and you have about 10^8 bases. Therefore the total number of cases is 4 to the something which may frighten you, but I can show it to you expressed as powers of 10: 4^2 is more than 10, so we obtain roughly $10^{60,000,000}$, which I could write down. And this is the total number of cases. Now let us calculate how probable it is that somebody who is only very remotely related to us, could somewhere else in the universe come into being just by chance. With 'remotely', I will be very generous, we and the apes agree in the DNA by more than 98%. Let us suppose a very remote similarity, where only every thousandth base is the same and the rest is different. In order to see whether such a structure can appear by accident, according to what we did before, we have to take the number of favourable cases, $10^{60,000,000-60,000}$ and divide by the number of total cases. And so again, you see, what you do is, you knock off three decimal points and you get for the probability $10^{-60,000}$. As this is very small, you say, well I do not want it happen here but only somewhere in the universe, so I have to multiply this probability with the number of stars I have in the universe. But $22-60,000$ is practically $-60,000$ and $10^{-60,000}$ is still practically nothing. That this happens by accident in this way is impossible. So there must be something else to it. And then what one does is that one goes over to a different law of evolution. Namely the laws of physics which we employed so far, were mixing—technically speaking. That is to say the probability distribution is dispersing all over the place and there are so many possibilities. What one does instead, is to take an evolution equation, which is not mixing but focussing. That is to say, it always follows a certain direction, as it is the case for Fisher's equation. It says in economics that the richer always gets richer and in evolution theory it says that the fitter always gets fitter. After a certain time only the fittest survive, and in economics always the richest has all the money. And in this way of changing the paradigm, you can explain the present evolution. This of course shows in some way, that scientific explanation cannot be beaten, because you can always adapt your description to what is actually happening and therefore you can always explain anything. On the other hand, you can always say, nevertheless I am surprised by it and I see this evolution follows a certain path. Whether it was done by the Almighty, using Fisher's equations or by something else, it follows this path and this, I think, is a very remarkable fact.