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TeV SCALE GRAVITY, MIRROR UNIVERSE AND ... DINOSAURS

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This is somewhat extended version of the talk given at the Gran Sasso Summer Institute: Massive Neutrinos in Physics and Astrophysics. It describes general ideas about mirror world, extra spatial dimensions and dinosaur extinction. Some suggestions are made how these seemingly different things can be related to each other.

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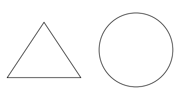
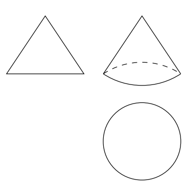
1. Introduction

The history of science in particular and the Human history in general teach us that it is not easy to answer a simple question [1] "What is truth?". Maybe because the truth usually has infinitely many aspects or projections to be grasped. The following example from [2] I like very much. Consider the two figures below.



Are they different? Certainly they are. This seems to be an indisputable truth. But if our wonderful divine gift — our imagination — will help us to escape bonds of the stiff two-dimensional logic we can see the following three-dimensional picture:



Now it is clear (an indisputable truth again) that these two figures, which originally appeared as two different objects, actually are just two different projections of the same thing — the cone. From the original two-dimensional picture alone it is impossible to establish with certainty whether these two figures are substantially different or not. With the help of imagination we can find as a viable option that these figures may have the common origin and represent in fact the one essence, but in order to prove the case one needs further information (some experiments?)

What follows is an attempt to answer Bludman's question [3] "Muß es sein?" with regard to the Mirror World. Until experiments firmly prove or disprove its existence, any answer will include a great deal of imagination by necessity. So I will describe things at first sight very different and not related to the Mirror World. I refer to your imagination to accept a possibility that these different tales are in fact fragments of the same story.

To demonstrate the importance of imagination, I will perform a little hocus-pocus now and find the Mirror World even in a simple arithmetical expression.

2. Arithmetics of the Mirror World

Let us begin with the (correct) expression

$$5 + 10 + 1 = 16.$$

Is it possible to find the Mirror World in this expression? Do not be hasty. At least a right-handed neutrino and SO(10) GUT can be found in this innocent expression, as Buccella had reminded us recently [4]. But after we catch sight of SO(10) from this expression it is possible for us to come across a more advanced SO(10)-arithmetics:

$$210 + 560 = 770.$$

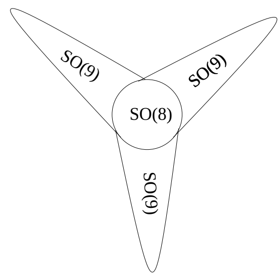
The remarkable fact about the fancy numbers above is that all these numbers are dimensions of some SO(10) irreducible representations (irreps). Now there is some general problem for you: find all SO(10) irreps such that the sum of the first two irrep dimensions matches exactly the dimension of the third irrep.

Maybe after some time you will find this problem a bit tricky and will decide firstly to try the analogous SO(9)-problem encouraged by the SO(9)-arithmetical observation

$$44 + 84 = 128. \tag{1}$$

If you are lucky enough, you will find a solution or will discover the one, given in the literature by Ramond *et al.* [5] and will understand that surprisingly equation (1) has its roots in the following (simple) triality structure of the F_4 exceptional Lie algebra:

$F_4 =$



Meanwhile you will learn a lot of beautiful mathematics like octonions, triality, Dynkin diagrams, Freudenthal-Tits magic square, Weyl chambers *etc.*

And after you have become so clever, it will strike you that SO(9) is nothing but a Wigner's little group associated to the massless degrees of freedom of eleven-dimensional supergravity. The irreps from (1) just form $N = 1$ supergravity super-multiplet in eleven dimensions, $\underline{44}$ representing gravitons, $\underline{84}$ — another massless bosonic field and $\underline{128}$ — the Rarita–Schwinger spinor. So the very equation (1) ensures supersymmetry, that is the equality between the bosonic and fermionic degrees of freedom.

But 11-dimensional $N = 1$ supergravity is just a low energy limit of much bigger theory, called M-theory [6]. And you will find for sure that this M(arvellous)-theory also gives in various limits all known string theories in ten dimensions, among them a heterotic string theory which leads in the low energy limit to the $E_8 \times E_8$ effective gauge theory, this second E_8 being nothing but the "shadow" world of mirror particles [6–8]!

After I have found the Mirror World even in some simple arithmetical expression, you will be not surprised, I hope, to hear that my next topic is about creatures very closely related to the massive neutrinos. And this creatures are dinosaurs.

3. The dinosaur mystery

First dinosaurs appeared on the Earth about 250 Myr (million years) ago, at the beginning of the Paleozoic Era, in a period of time geologists called "Triassic". Shortly after their appearance, they grew in size as well as in numbers and types and dominated the food chain nearly for 200 Myr. Some dinosaurs were very powerful creatures. Indeed very powerful and very big. But this did not help them very much when their doomsday came at the end of the Cretaceous Period, the time period they dominated on the Earth. Something very mysterious happened on the Earth about 65 Myr ago and dinosaurs suddenly (in a geological time scale) disappeared: their fossils were found throughout the Mesozoic Era but not in the rock layers of the Cenozoic Era. The first period of this new Era is called "Tertiary" by geologists, so the dinosaur extinction is known as the Cretaceous–Tertiary or K–T extinction. In fact dinosaurs were not the only victims of this extinction — about 85% of all species inhabiting the Earth at that time went extinct, among them many marine species.

Such mass extinctions happened several times in the Earth's history. Let us mention some major extinctions [9]:

- The Precambrian extinction 650 Myr ago — maybe the first great extinction. About seventy percent of the dominant Precambrian flora and fauna perished.
- The Cambrian extinction 500 Myr ago — about 50% of all animal families went extinct.
- The Devonian extinction 360 Myr ago — the crisis primarily affected the marine community, having little impact on the terrestrial flora.
- The Permian extinction 248 Myr ago — the greatest mass extinction ever recorded in the Earth's history. About 50% of all animal families perished, as well as about 95% of all marine species and many trees.

One can imagine at least two reasons why it is interesting to answer the question "what killed the dinosaurs?" First of all, without extinctions we would not be here. Extinction of species is a common companion of evolution. A fossil record documents some 2×10^5 such extinctions. Only $\sim 5\%$ of all animal and plant species, ever originated on the Earth, are alive today. But this natural extinction process is local and gradual and do not effect much the evolution. On the contrary, mass extinctions are events of global magnitude which nearly destroy the life on the Earth, but after them the evolution is boosted ahead: new varieties of species appear which flourish and promptly occupy the vacant ecological niches. The evolution seems to be a process of punctuated equilibrium. And this process was certainly punctuated by some global event 65 Myr ago and as a result the dinosaur era was changed by the mammal era — the event clearly of great importance for humankind. But this is a "positive" aspect of mass extinctions. There is a negative one too. If this unfortunate thing happened to dinosaurs (and many other less prominent species), there is no guarantee that the same will not happen to us (humankind) and so it is not excluded that we could be also found as fossils someday — the perspective, you certainly do not like. But "evolution loves death more than it loves you or me. This is easy to write, easy to read, and hard to believe. The words are simple, the concept clear– but you do not believe it, do you? Nor do I. How could I, when we are both so lovable? Are my values then so diametrically opposed to those that nature preserves? ...we are moral creatures in an amoral world. The universe that suckled us is a monster that does not care if we live or die– does not care if it itself grinds to a halt. It is fixed and blind, a robot programmed to kill. We are free and seeing; we can only try to outwit it at every turn to save our skins" [10]. And we can hope to save our skins only if we understand where the danger comes from.

Many theories were suggested to explain the dinosaur mystery. They can be divided into two general groups [11]. The first kind of theories operate with the extinction causes which are intrinsic (that is Earth based) and gradual (last several million years), like volcanism and plate tectonics. These are favorite theories of paleontologists and roughly a half of geologists attracted by the problem of dinosaur extinction. Another half of geologists and the most astronomers and physicists prefer extinction causes which are extrinsic (of cosmic nature) and sudden, like an asteroid or comet impact.

The asteroid impact as a cause of the K–T extinction was suggested by Alvarez *et al.* [12] and is the most popular hypothesis today. According to this scenario, the impact of a large object (an asteroid or a comet with > 10 km diameter) 65 Myr ago threw up a huge dust cloud which remained for weeks and blocked sunlight worldwide. Impact(s) may also have triggered rounds of volcanic eruptions. As a result, global and less lasting climate changes, impact-induced global wildfires, acid rains *etc.* effected Earth's ecology of that time enough to force the dinosaurs to their end [13].

The popularity of this hypothesis is based not only on the pagan nature of the contemporary science. I mean its passion of creating various idols, and Luis Alvarez was one of such idols in 1980 because of his Nobel prize. Simply there is some grave objective evidence that the impact really happened at the Cretaceous–Tertiary boundary. The most important evidence is iridium anomaly discovered by Alvarez *et al.* [12].

It seems there is a thin band of deposit of clay at the Cretaceous–Tertiary boundary around the world highly enriched with iridium. This rare-earth element is quite sparse in Earth's crust but common in meteorites. So this iridium anomaly, which was found by Alvarez *et al.* initially in marine sediments in Italy and afterwards confirmed in both continental and marine sediments at more than 100 areas world-wide, can be considered as the first physical evidence that some cosmic intruder hit the Earth 65 Myr ago.

In fact iridium can be extruded by volcanos from Earth's core where it is more abundant. And it is known [14] that just about 65 Myr ago India, which was an isolated island at that time drifting towards its collision with Asia, met the head of a mantle plume, molten rock masses extending from Earth's core-mantle interface upward to the base of Earth's crust. This mantle plume found its way through India's crust producing the Deccan

Traps volcanism, the greatest volcanic episodes in the Earth's history ever known. The hotspot volcano which had produced Deccan Traps still exists today on Reunion Island and even now is releasing iridium [15]!

Therefore one needs some extra evidence to discriminate between impact and volcano origin of iridium. These extra evidences are microtektites (very small glass spheres) strewn fields world-wide and the presence of quartz grains with multiple sets of shock lamellae (shocked quartz) in the very same clay layer between Cretaceous and Tertiary sediments. They both are common products of violent explosions followed to hypervelocity impacts and therefore testify in favor of impact, not volcanic origin of iridium. The last nail into coffin for competitive theories was the discovery that the Chicxulub crater located in the Yucatan Peninsula (Mexico) was in fact the long sought K–T crater [16].

To summarize, there is a little doubt today (especially among astronomers and physicists) that a large asteroid or comet collided the Earth 65 Myr ago. It cannot be inferred with certainty that this was the only cause of the K–T extinction, or even that it was the major cause. Other factors, like Deccan Traps volcanism, could also play a significant role. Note that the competitive ideas suggested to resolve the dinosaur mystery do not necessarily exclude each other. It may happen that they all contain just different projections of the same truth. An interesting example how extraterrestrial and volcano ideas can be unified is given by Dar [17]. Inspired by the Hubble Space Telescope discovery that the central star of the Helix Nebula is surrounded by a ring of about 3500 giant comet-like objects, he speculates that similar massive objects can be present in outer solar system. Gravitational perturbations (for example by passing field stars) can change their orbits and bring them into the inner solar system. Near encounter of the Earth with such "visiting planet" can generate gigantic water tidal waves of ~ 1 km height and crustal tidal waves of ~ 100 m height. Flexing the Earth by ~ 100 m will release $\sim 10^{34}$ ergs heat in Earth's interior in a short time and may trigger the gigantic volcanic eruptions. Note that the Jupiter's moon Io owes its volcanic activity (the strongest in the solar system) to the frictional heating due to tidal forces.

But now that's enough about dinosaurs. To proceed and show how dinosaur extinction is related to massive neutrinos, the main topic of our conference, we need another mystery story.

4. The parity mystery

It is well known that the weak interactions do not respect $\boldsymbol{P}$-invariance. To imagine how strange this situation is, let us state this $\boldsymbol{P}$-noninvariance in another way. The image of our world in a $\boldsymbol{P}$-mirror does not look like the original. For example, if we take 15 degrees of freedom of the first quark-lepton generation, after reflection in the $\boldsymbol{P}$-mirror we will have (color degrees of freedom is not indicated for quarks):

$$\begin{array}{ccccccc} u_{\mathrm{L}} & d_{\mathrm{L}} & e_{\mathrm{L}} & \nu_{\mathrm{L}} & u_{\mathrm{R}} & d_{\mathrm{R}} & e_{\mathrm{R}} \\ \hline u_{\mathrm{R}} & d_{\mathrm{R}} & e_{\mathrm{R}} & & u_{\mathrm{L}} & d_{\mathrm{L}} & e_{\mathrm{L}} \end{array} \qquad \boldsymbol{P}$$

Therefore we are lacking right-handed neutrino state for the world to be left–right symmetric! Does this fact mean that the Nature distinguishes left and right? Not necessarily. In the quantum theory space inversion is represented by some quantum-mechanical operator $\boldsymbol{P}$. But different observers can choose not only different conventions about what is left or right reference frame, but also different bases in the internal symmetry space of the system. Therefore the operator $\boldsymbol{P}$ is determined up to an internal symmetry operator $\boldsymbol{S}$. In other words, all operators $\boldsymbol{PS_1},\ \boldsymbol{PS_2},\ \boldsymbol{PS_3},\ldots$ are equivalent and any of them may be selected as representing space inversion in the Hilbert space of the quantum system. Now if we find some good enough internal symmetry $\boldsymbol{S}$, so that $\boldsymbol{PS}$ is conserved, the world will be still invariant with respect to the $\boldsymbol{PS}$-mirror (and this mirror is as good as $\boldsymbol{P}$-mirror itself for representing space inversion quantum mechanically). This subtlety in the quantum-mechanical realization of the space inversion transformation was recognized shortly after the experimental discovery of the parity non-conservation and it was suggested [18] that the charge conjugation $\boldsymbol{C}$ could be the very internal symmetry needed. Indeed the world looks symmetric when reflected in the $\boldsymbol{CP}$-mirror:

$$\begin{array}{cccccccccccccc} u_{\mathrm{L}} & d_{\mathrm{L}} & e_{\mathrm{L}} & \nu_{\mathrm{L}} & u_{\mathrm{R}} & d_{\mathrm{R}} & e_{\mathrm{R}} & u_{\mathrm{R}}^C & d_{\mathrm{R}}^C & e_{\mathrm{R}}^C & \nu_{\mathrm{R}}^C & u_{\mathrm{L}}^C & d_{\mathrm{L}}^C & e_{\mathrm{L}}^C \\ \hline u_{\mathrm{R}}^C & d_{\mathrm{R}}^C & e_{\mathrm{R}}^C & \nu_{\mathrm{R}}^C & u_{\mathrm{L}}^C & d_{\mathrm{L}}^C & e_{\mathrm{L}}^C & u_{\mathrm{L}} & d_{\mathrm{L}} & e_{\mathrm{L}} & \nu_{\mathrm{L}} & u_{\mathrm{R}} & d_{\mathrm{R}} & e_{\mathrm{R}} \end{array} \qquad \boldsymbol{CP}$$

Therefore no absolute definitions of left and right are possible in the world where $\boldsymbol{CP}$ is an unbroken symmetry.

But we know that in our world $\boldsymbol{CP}$ is not an unbroken symmetry. So we are left with a strange opportunity that left and right have absolute meanings in our world, unless we manage to find some other good internal symmetry which will restore the space inversion invariance of the world. But there is no obvious candidate for such internal symmetry. Therefore the scientific community simply became reconciled to the parity non-invariance of Nature. Moreover, the belief that the only good symmetries are the proper Poincaré symmetries became some kind of dogma, as strong as there was the opposite belief before Lee and Yang's seminal paper [19] that the space inversion and time reversal should also be the exact symmetries of Nature. This prompt rejection of improper Poincaré symmetries looks especially strange if we remember that an internal symmetry which can restore the invariance with respect to the full Poincaré group was in fact suggested in the very paper [19] of Lee and Yang. Maybe their proposal did not gain popularity because at first sight it was no less strange than the suggestion that the left and right reference frames are not equivalent. You can restore the equivalence and hence save the space inversion invariance but you have to pay a price, and the price seems to be too high: duplication of the world. For any ordinary particle, the existence of the corresponding "mirror" particle is postulated. These mirror particles are sterile with respect to the ordinary gauge interactions but interact with their own mirror gauge particles. Vice versa, ordinary particles are singlets with respect to the mirror gauge group. This mirror gauge group is an exact copy of the Standard Model $\mathrm{G}_{WS} = \mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$ group with only difference that left and right are interchanged when we go from the ordinary to the mirror particles. Therefore the mirror weak interactions reveal an opposite $\boldsymbol{P}$-asymmetry and hence in such an extended universe $\boldsymbol{MP}$ is an exact symmetry, where $\boldsymbol{M}$ interchanges ordinary and mirror particles, and therefore there is no absolute difference between left and right. This universe looks symmetric when reflected in the $\boldsymbol{MP}$-mirror:

$$\begin{array}{c} u_\mathrm{L}\;\; d_\mathrm{L}\;\; e_\mathrm{L}\;\; \nu_\mathrm{L}\;\;\; u_\mathrm{R}\;\; d_\mathrm{R}\;\; e_\mathrm{R}\;\;\; u'_\mathrm{R}\;\; d'_\mathrm{R}\;\; e'_\mathrm{R}\;\; \nu'_\mathrm{R}\;\; u'_\mathrm{L}\;\; d'_\mathrm{L}\;\; e'_\mathrm{L} \\ \hline\hline u'_\mathrm{R}\;\; d'_\mathrm{R}\;\; e'_\mathrm{R}\;\; \nu'_\mathrm{R}\;\; u'_\mathrm{L}\;\; d'_\mathrm{L}\;\; e'_\mathrm{L}\;\;\; u_\mathrm{L}\;\; d_\mathrm{L}\;\; e_\mathrm{L}\;\; \nu_\mathrm{L}\;\; u_\mathrm{R}\;\; d_\mathrm{R}\;\; e_\mathrm{R} \end{array} \quad \boldsymbol{MP}$$

After a decade, Kobzarev, Okun and Pomeranchuk returned to this idea [20]. It was shown that mirror particles should interact only extremely weakly with the ordinary particles to evade conflict with experiment. In fact only gravity provides a bridge between two worlds. But gravitational interactions are very weak. So it is not easy to check the mirror world hypothesis. That's why the idea remained not popular and even essentially unknown until recently, as illustrated by the fact that it was rediscovered by Foot, Lew and Volkas [21] 25 years later!

In fact there are also other ways, besides gravity, to connect these two worlds. For example, gauge invariant and renormalizable ordinary-mirror mixing is allowed for neutral particles like Higgs, γ and Z gauge bosons, and neutrinos.

Higgs — mirror Higgs mixing can modify significantly the interactions of the Higgs boson [22]. But we have to wait until the discovery of the Higgs scalar to test this possibility.

Photon — mirror photon kinetic mixing term can originate if there exists mixed form of matter (connector) carrying both ordinary and mirror electric charges [23]. Even for a very heavy connector, the induced mixing is expected to be significant and as a result mirror charged particles from the mirror world acquire a small ($\sim 10^{-3}e$) ordinary electric charge. Such millicharged particles have never been found [24]. But the most stringent bound on the mixing comes from the possibility for positronium to oscillate into mirror positronium and disappear [25].

The neutrino case is the most interesting. Although a possible connection between neutrino properties and mirror world was noticed earlier [22,26–28], the real understanding that the mirror world provides a way to reconcile observed neutrino anomalies (solar neutrino deficit, the atmospheric neutrino problem, Los Alamos evidence for neutrino oscillations) arose after two recent papers by Foot and Volkas [29], Berezhiani and Mohapatra [30]. The latter work considers an asymmetric mirror world with spontaneously broken $\boldsymbol{MP}$. At present this variant of the mirror world scenario, further developed in several subsequent publications, is not excluded by observations. But I will be surprised very much if eventually just this asymmetric mirror world proves to be correct. Why, just imagine, would God have invented the mirror world if parity remains broken?

In the minimal mirror extension of the Standard Model, we have just two neutrino Weyl states $\nu_{\rm L}$ and $\nu'_{\rm R}$ (mirror particles are denoted by prime throughout the paper) per generation. If Majorana masses are allowed, the most general neutrino mass matrix consistent with MP-parity conservation is [29]

$$\left[\overline{\nu_{\rm L}}\,,\ \overline{(\nu'_{\rm R})^C}\right]\left(\begin{array}{cc} M & m \\ m & M^* \end{array}\right)\left(\begin{array}{c} (\nu_{\rm L})^C \\ \nu'_{\rm R} \end{array}\right) + \text{H.c.}\,, \tag{2}$$

where the Dirac mass m is real. The mass eigenstates are the maximal mixtures of ordinary and mirror neutrinos no matter how small the initial mixing parameter m is:

$$\nu_{\rm L}^+ = \frac{1}{\sqrt{2}}\left(\nu_{\rm L} + (\nu'_{\rm R})^C\right), \qquad \nu_{\rm L}^- = \frac{1}{\sqrt{2}}\left(\nu_{\rm L} - (\nu'_{\rm R})^C\right).$$

In fact this maximality of mixing is a quite general and very important consequence of the space inversion symmetry restoration through mirror world and provides a clear experimental signature of this scenario [29].

The mirror world can also naturally accommodate very small neutrino masses by MP-symmetric variant of the standard seesaw model [29], or it can even provide an alternative explanation why neutrino masses are so small [28]. Let us consider the latter case. In order that the neutrino not be discriminated as compared to the corresponding charged lepton, let us assume that in addition to the $\nu_{\rm L}$ and $\nu'_{\rm R}$ states there exist a right-handed neutrino $\nu_{\rm R}$ and its left-handed mirror partner $\nu'_{\rm L}$, which are $\mathrm{G}_{WS}\otimes\mathrm{G}_{WS}$ singlets. Such states naturally arise if, for example, gauge group of the mirror world $\mathrm{G}_{WS}\otimes\mathrm{G}_{WS}$ is a low energy remnant of $\mathrm{SO}(10)\otimes\mathrm{SO}(10)$ grand unification. In such a grand unified mirror world, some early stages of symmetry breaking (for example SO(10) $\otimes$ SO(10) $\to$ SU(5) $\otimes$ SU(5)) can generate a large $\nu_{\rm R} - \nu'_{\rm L}$ mixing. Besides, ordinary electroweak Higgs mechanism and its mirror partner will lead to neutrino and mirror neutrino masses. Therefore we expect the following neutrino mass terms

$$-\mathcal{L}_{\rm mass} = M(\overline{\nu_{\rm R}}\nu'_{\rm L} + \overline{\nu'_{\rm L}}\nu_{\rm R}) + m(\overline{\nu_{\rm L}}\nu_{\rm R} + \overline{\nu_{\rm R}}\nu_{\rm L} + \overline{\nu'_{\rm R}}\nu'_{\rm L} + \overline{\nu'_{\rm L}}\nu'_{\rm R})\,, \qquad (3)$$

where m is expected to be of the order of the charged lepton mass of the same generation, while the expected value of M is 10^{14}–10^{15} GeV. Among the mass eigenstates of (3) (physical neutrinos denoted by tilde) we have the following Weyl states

$$\tilde\nu_{\rm L} = \cos\theta\,\nu_{\rm L} - \sin\theta\,\nu'_{\rm L}\,, \qquad \tilde\nu'_{\rm R} = \cos\theta\,\nu'_{\rm R} - \sin\theta\,\nu_{\rm R} \sim \boldsymbol{MP}(\tilde\nu_{\rm L})\,,$$

where $\theta \approx m/M$ is very small. These Weyl states constitute a very light Dirac neutrino $(\tilde\nu_{\rm L}, \tilde\nu'_{\rm R})$ with the mass $\sim m^2/M$. This neutrino is a rather bizarre object — its left-handed component inhabits mostly our ordinary world, while right-handed component prefers the mirror world intriguing mirror physicists. Alternatively, you can notice that, because $\overline{\tilde\nu'}_{\rm R}\tilde\nu_{\rm L} = \overline{(\tilde\nu_{\rm L})^C}(\tilde\nu'_{\rm R})^C$, this ultralight-neutrino mass term

$$m\frac{m}{M}\left(\overline{\tilde\nu'_{\rm R}}\tilde\nu_{\rm L} + \overline{\tilde\nu_{\rm L}}\tilde\nu'_{\rm R}\right)$$

can be considered as a degenerate limit of (2) with zero Majorana masses and you can work, if you prefer, in terms of (degenerate) maximally mixed $\boldsymbol{CMP}$ and mass eigenstates

$$\nu_{\rm L}^+ = \frac{1}{\sqrt2}\left(\tilde\nu_{\rm L} + (\tilde\nu'_{\rm R})^C\right), \qquad \nu_{\rm L}^- = \frac{1}{\sqrt2}\left(\tilde\nu_{\rm L} - (\tilde\nu'_{\rm R})^C\right).$$

Besides neutrino oscillations, there are some other observed phenomena which can be also interpreted as supporting mirror world hypothesis. It is well known that there is a lot of dark matter in our universe and the mirror matter can constitute a considerable fraction of this dark universe [31]. It is even possible that mirror stars have been already observed as gravitational microlensing events [28, 32]. Recent Hubble Space Telescope star counts revealed the deficit of local luminous matter [33] predicted by Blinnikov and Khlopov many years ago [34] as a result of mirror stars existence. Note however that Hipparchos satellite data [35] have not confirmed the deficit of visible matter. Mirror matter was evoked to explain some mysterious properties of Gamma-ray Bursts [36]. Just during our conference the paper by Mohapatra, Nussinov and Teplitz appeared about the latter subject [37]. This paper provokes a thought that maybe the straightest road from mirror world to the ordinary one lays through extra dimensions. So we turn our narrative now towards extra dimensions.

5. The hierarchy mystery

The energy scale where gravity becomes strong and quantum gravity effects are essential is given by the Planck mass. This mass can be estimated as follows. Suppose two particles of equal masses m are separated at a distance which equals to the corresponding Compton wavelength $\lambda = 1/m$. If the gravitational interaction energy of the system $G_N m^2/\lambda = G_N m^3$ is of the same order as the particle rest mass m, then the former cannot be neglected. This gives for the Plank mass

$$M_{\rm Pl} = \frac{1}{\sqrt{G_N}} \approx 10^{19}\ {\rm GeV}.$$

Huge difference between this quantum gravity energy scale and the electroweak scale $E_{\rm EW} \approx 10^2$ GeV is astonishing and constitutes the so called hierarchy problem. There is also a gauge hierarchy problem: the Grand Unification scale $E_{\rm GUT} \approx 10^{16}$ GeV is very big compared to $E_{\rm EW}$. Any successful theory should not only explain these hierarchies, but also provide some mechanism to protect them against radiative corrections. Recently an interesting idea was suggested by Arkani-Hamed, Dimopoulos and Dvali [38] how to deal with the hierarchy problem. Certainly, there will be no problem, if there is no hierarchy. But how can we lower the quantum gravity scale so that the hierarchy disappears? It turns out that this is possible if extra spatial dimensions exist with big enough compactification radius.

Suppose that besides the usual x, y, z coordinates there exist some additional spatial coordinates $x_1, \ldots, x_n$, which are compactified on circles with a common (for simplicity) compactification radius R. In such a world with toroidal compactification, the gravitational potential, created by an object of mass m, should be periodic in the extra n-dimensions. That is, it should be invariant under replacements $x_i \to x_i \pm 2\pi R$. Besides it should vanish at spatial infinity and obey the $(n+3)$-dimensional Laplace equation. These requirements are satisfied by the following function [39]

$$V = -\sum_{n_1,\ldots,n_n} \frac{\tilde{G}_N m}{\left[r^2 + \sum\limits_{i=1}^{n} (x_i - 2\pi R n_i)^2\right]^{(n+1)/2}},$$

where $\tilde{G}_N$ is the Newton constant for $n+4$ space-time dimensions and $r^2 = x^2 + y^2 + z^2$ is the usual three-dimensional radial distance. If the compactification radius R is very large, only the term with $n_1 = 0, \ldots, n_n = 0$ survives in the sum and we get the Newton law in $n+4$ dimensions:

$$V \approx -\frac{\tilde{G}_N m}{\tilde{r}^{n+1}}, \tag{4}$$

where $\tilde r = \sqrt{r^2 + \sum\limits_{i=1}^{n} {x_i}^2}$. But if $R \ll r$, the sum can be approximated by an integral

$$V \approx -\frac{\tilde G_N m}{(2\pi R)^n} \int d^{(n)}\vec x \frac{1}{(r^2+\vec x^2)^{(n+1)/2}} \sim -\frac{\tilde G_N}{R^n}\,\frac{m}{r}\,.$$

Therefore for the conventional 4-dimensional Newton constant we have

$$G_N \sim \frac{\tilde G_N}{R^n}\,.$$

On the other hand, the fundamental multidimensional quantum gravity scale $\tilde M_{\rm Pl}$ is now determined from

$$|\tilde M_{\rm Pl} V(\frac{1}{\tilde M_{\rm Pl}})| \sim \tilde M_{\rm Pl}\,,$$

where the potential V is given by the equation (4), and we have

$$\tilde M_{\rm Pl} = \left[\tilde G_N\right]^{-\frac{1}{n+2}}\,.$$

The last two relations indicate

$$\frac{M_{\rm Pl}}{\tilde M_{\rm Pl}} \sim \left(\frac{R}{R_0}\right)^{\frac{n}{2}}\,, \tag{5}$$

where $R_0 = 1/\tilde M_{\rm Pl}$ and $R_0 \approx 10^{-19}$ m (m — one meter), if the fundamental quantum gravity scale $\tilde M_{\rm Pl}$ is in a few TeV range. Therefore the initial $M_{\rm Pl}/E_{\rm EW}$ hierarchy problem can be traded to another hierarchy: the largeness of the compactification radius compared to R_0. Namely, we get from (5) the corresponding compactification radius as

$$R \sim 10^{\frac{32}{n}-19}\ {\rm m}\,.$$

For one extra dimension this means modification of the Newton's gravity at scales $R = 10^{13}$ m and is certainly excluded. But already for $n = 2$, $R \sim 10^{-6}$ m — just the scale where our present day experimental knowledge about gravity ends.

Although gravity was not checked in the sub-millimeter range, Standard Model interactions were fairly well investigated far below this scale. Therefore if the large extra dimensions really exist, one needs some mechanism to prevent Standard Model particles to feel these extra dimensions.

Remarkably, there are several possibilities to ensure their confinement at a 3-dimensional wall in the multidimensional space [40]. Just to illustrate one of them, let us consider a toy model [41, 42] in the (3+1)-dimensional space-time with the Lagrangian

$$\mathcal{L} = \bar{\psi} i\hat{\partial}\psi - h\phi\bar{\psi}\psi + \tfrac{1}{2}(\partial_\mu\phi)^2 - \lambda(\phi^2 - v^2)^2 \,. \tag{6}$$

This Lagrangian possesses Z_2 symmetry

$$\psi \to i\gamma_5\psi, \qquad \phi \to -\phi,$$

which is spontaneously broken in the true vacuum state where $\langle\phi\rangle = v$ or $\langle\phi\rangle = -v$. We assume that the spinor–scalar interaction term $h\phi\bar{\psi}\psi$ is small, so in a good approximation the equation of motion for the field ϕ looks like

$$\partial_\mu\partial^\mu\phi = -4\lambda\phi(\phi^2 - v^2) \,. \tag{7}$$

It is easy to check that (7) has a kink-like solution which depends only on the z-coordinate

$$\tilde{\phi}(z) = v \tanh\left(\sqrt{2\lambda} v z\right).$$

This solution is a domain wall interpolating between two different vacuua $\langle\phi\rangle = v$ and $\langle\phi\rangle = -v$. Its thickness in the z direction is of order of m^{-1}, where $m = \sqrt{2\lambda} v$.

Let us consider now the fermion in this kink-like background. The equation of motion which follows from(6) is

$$i\hat{\partial}\psi = h\tilde{\phi}(z)\psi \,. \tag{8}$$

This last equation has a factorized solution

$$\psi = \nu(x, y) f(z),$$

where $f(z)$ is a scalar function and the $\nu(x, y)$ spinor satisfies (note that γ_3 is anti-Hermitian)

$$i\hat{\partial}\nu(x, y) = 0, \qquad \gamma_3\nu(x, y) = i\nu(x, y).$$

For $f(z)$, equation (8) then gives

$$\frac{df(z)}{dz} = -h\tilde{\phi}(z) f(z),$$

its solution with $f(0) = 1$ being

$$f(z) = \exp\left\{-h\int_0^z \tilde{\phi}(z)dz\right\} = \exp\left\{-\frac{h}{\sqrt{2\lambda}} \ln\left(\cosh zm\right)\right\}.$$

We see that

$$\psi=\nu(x,y)\exp\left\{-\frac{h}{\sqrt{2\lambda}}\ln\left(\cosh zm\right)\right\}$$

describes a massless "flat" fermion $\nu(x,y)$ localized on the domain wall, the localization scale determined by the fermion-scalar interaction strength h.

To summarize, the hierarchy mystery maybe indicates the following fascinating structure of our world: the Standard Model particles (and hence human observers) are stuck on a wall ("3-brane") in the higher ($\geq 4+n$) dimensional space-time. On the contrary, gravity propagates freely in the remaining space (the bulk) and feels large ($\sim 10^{-6}$ m) compact extra dimensions. In the string theory framework, this picture is naturally achieved if the ordinary particles correspond to endpoints of open strings attached to the brane, while gravity, represented by closed strings, can propagate in the bulk. The most surprising thing about this crazy idea is that it doesn't come in immediate conflict with known experimental facts [40, 43, 44].

I would like to end this chapter with some of my personal experience with extra dimensions. Some times ago I had sent an e-mail letter to my friend in Chicago. Soon I received the answer saying "I have received a message from you but I don't know to which Sasha it is addressed (I don't know about any Sasha now in Milano)". I was surprised, not so much by what my letter went to Milan instead of Chicago, but by the fact that the answer was from Andrea Gamba, and while preparing my diploma theses at my university years I had read a very interesting paper by Gamba [45] about peculiarities of the eight-dimensional space. I was intrigued and asked him if he was the very eight-dimensional Gamba. The answer was "It's really a mystery how I received your letter; unfortunately I don't know about 8-dimensional space, in 1967 I was 5 years old... But certainly your message passed through some extra dimension!"

So personally I'm quite convinced about existence of extra dimensions. I was so much astonished by the coincidence decsribed above that I even wrote a scientific paper [46] about peculiarities of the eight-dimensional space and its possible connection to the generation problem — this paper can be considered as a material evidence of communications through extra dimensions. But now it is time to stop making fun and ask what profit the large extra dimensions can give for the mirror world.

6. Extra dimensions and the mirror universe

Gravity is the main connector between our and mirror worlds. Therefore, if it becomes strong at high energies of about few TeV, the immediate consequence will be a possibility to produce mirror particles at future high energy colliders via virtual graviton exchange. The typical total cross-sections are [47]

$$\sigma \sim \frac{s^3}{\Lambda^8} \sim (\text{few} \quad \text{pb}) \left(\frac{s}{\text{TeV}^2}\right)^3 \left(\frac{\text{TeV}}{\Lambda}\right)^8 ,$$

where $\Lambda \sim 1\text{TeV}$ is an ultraviolet cutoff energy for the effective low-energy theory, presumably of the order of the bulk Planck mass [48]. These cross sections are quite sizeable, but unfortunately there is no clear experimental signature for such kind of events. May be more useful signature have reactions accompanied by the initial-state radiation but we expect severe background problems here, in particular from the real graviton emission. Therefore the TeV-scale quantum gravity can allow quite effective mirror matter production at future TeV-range colliders, but it will be very difficult to convince skeptics that the mirror particles have been really produced.

Another interesting effect is quarkonium — mirror quarkonium oscillations. As a result, heavy C-even quarkonia can oscillate into their mirror counterparts, and hence disappear from our world. Unfortunately the expected probabilities are very small [47]. For example, the probability for χ_{b2} state to oscillate into its mirror partner is about 3×10^{-14}.

The most promising effect is connected to mirror supernova, because some part of a mirror supernova energy will be released in our world too. In [47] $e'^+e'^- \to e^+e^-$, $\gamma\gamma$ reactions were considered as a tool to transfer energy from the mirror to the ordinary sector. The resulting ordinary energy emissivity per unit volume per unit time of a mirror supernova core with a temperature T is given by the thermal average over the Fermi–Dirac distribution and was found to be [47]

$$\dot{q} = \frac{6T^{13}}{25\pi^3\Lambda^8}[I_5(\nu)I_6(-\nu) + I_5(-\nu)I_6(\nu)] , \tag{9}$$

where

$$\nu = \frac{\mu_e}{T} \qquad \text{and} \qquad I_n(\nu) = \int\limits_0^\infty dx \frac{x^n}{\exp{(x+\nu)}+1} ,$$

μ_e being the chemical potential for mirror electrons in the mirror-supernova core.

Let us compare (9) to the neutrino emissivity by supernova [49] (only the leading term is shown)

$$\dot{q}_{\nu\bar{\nu}} = \frac{2G_{\mathrm{F}}^2T^9}{9\pi^5}(C_V^2 + C_A^2)[I_3(\nu)I_4(-\nu) + I_3(-\nu)I_4(\nu)] , \tag{10}$$

where $C_A = \frac{1}{2}$, $C_V = \frac{1}{2} + 2\sin^2\Theta_W$ and G_{F} is the Fermi coupling constant. For the core temperature $T = 30$ MeV, chemical potential $\mu_e \approx 345$ MeV and $\Lambda \sim 1$ TeV, the last equations (9) and (10) give

$$\frac{\dot{q}}{\dot{q}_{\nu\bar{\nu}}} \approx 1.4 \times 10^{-16}.$$

As expected, we get a very small number. But in the first ~ 10 seconds the neutrino luminosity from a supernova is enormous [50]: $L_{\nu\bar{\nu}} \approx 3 \times 10^{45} W$ for each species of neutrino. And even 1.4×10^{-16}-th part of $L_{\nu\bar{\nu}}$ is thousand times larger than the solar luminosity!

Therefore mirror supernovas can be seen by ordinary observers, at least for some seconds after their birth. Note that according to [37] we are already observing light from mirror supernovas as gamma ray bursts!

We tacitly assumed above that the ordinary and mirror matter are located on the same 3-brane. For space-times with extra dimensions this is not necessarily the only possibility. In fact you can imagine a situation then different worlds are located on different 3-branes [51] (or even on branes with dimensionality other than 3). But I would be careful of using the nickname "mirror" for particles living on different brane. Maybe "shadow world" or "parallel world" is more appropriate in this case. I prefer to reserve the name "mirror world" for situations which mean the exact parity symmetry. But how the exact parity invariance can be reconciled with parallel worlds? A priori one cannot expect any symmetry between parallel worlds which are located on different branes. For me the only natural possibility is to ensure the parity symmetry for separate brane worlds. I think this may be achieved if particles can't cross the brane (in the low energy approximation) and are trapped on the different surfaces of the brane. Then the parity transformation will involve a transition from one brane surface to another. Therefore the mirror particles are just particles located on the another surface of our brane and so are not separated from the ordinary world very much in extra dimension, if the brane is thin. In this case one should expect the same low scale quantum gravity effects as discussed at the beginning of this chapter for the situation then the ordinary and mirror particles inhabit the same brane.

This idea is not as wild as it seems at first sight. Let me recall you an interesting condensed matter analogy: vierbein domain walls in superfluid ^{3}He–A film [52]. Such domain wall divides the bulk into two classically separated "worlds": no quasiparticle can cross the wall in the classical limit. But "Planck scale physics" allows these worlds to communicate and quasiparticles with high enough energy can cross the wall. Moreover, the left-handed chiral quasiparticle becomes right-handed when the wall is crossed!

If you want a really cool crazy idea — here it is: the mirror world without mirror particles [53]. To illustrate this idea, imagine you are the king of ants living in a two-dimensional flatland. One day your main court astrologist gives you a piece of exciting news that there is a deep sense in the notions of left and right, because nature does not respect parity symmetry and so the absolute meaning of the left, as the side preferred by stars, can be established. You immediately decide to notify your subject ants to what is left — the lucky side. So you send couriers with this mission throughout your kingdom. It may happen however that your world has a non-trivial global structure in the higher dimensional space and constitutes, for example, a Möbius strip. Then after some time one of your couriers can be found in a land, your main astrologist calls the land of shadows. You can not see him but can communicate with him using gravity. Gravitationally you feel as if he were somewhere very close. And really he is just beneath you on the Möbius strip — see Fig. 1 below [54].

Fig. 1. The Möbius world.

But you are flat, as are all of your subjects, and so have no idea about extra dimensions. You cannot say that your courier ant is turned upside-down, because he is two-dimensional. And his two-dimensional appearance, checked by gravity, looks the same as for all other ants. Simply in his zeal to fulfill your order he traveled too far away. And everybody knows in your kingdom that if you travel long enough way you will return the same place, but will return as an invisible shadow. Your main astrologist says that one can reach the land of shadows after very long journey. But anyway this land of shadows is a part of your kingdom — nobody, even your main astrologist, can tell you where the ordinary land ends and the land of shadows begins. So naturally you want your shadow subjects also to have the correct notion to what is the left side. And here a great surprise is awaiting you. For your main astrologist horror, you shadow courier indicates completely different side as the left side — the side which originally was marked as right by the very same courier before he left the court.

Hence in a such Möbius world the absolute difference between left and right has meaning only locally. No such difference can be established globally — the world as the whole is parity invariant!

If you do not like worlds to have edges, you can consider, for example, a Klein's bottle universe instead. In this case you need at least four space dimensions to realize such (two-dimensional) world without self-intersections.

7. Nemesis — the dark (matter) sun?

But, for goodness's sake, what have in common all these mirror worlds and extra dimensions with dinosaurs? — you may ask. To explain this, we need one more (in fact my favorite) dinosaur extinction theory [55]:

"There is another Sun in the sky, a Demon Sun we cannot see. Long ago, even before great grandmother's time, the Demon Sun attacked our Sun. Comets fell, and a terrible winter overtook the Earth. Almost all life was destroyed. The Demon Sun has attacked many times before. It will attack again."

It is a very nice theory, having almost mythical power, isn't it? But such explanation would be enough in some primitive society, not spoiled by the science and civilization. You need more scientific story, I suspect. And the scientific story begins with the question: are mass extinctions periodic?

"Most discoveries in physics are made because the time is ripe" [56]. And not only in physics. Although Fischer and Arthur had already suggested a 32-Myr periodicity in marine mass extinctions [57], it took about seven years for the subject to become popular. And this happened when Raup and Sepkoski's seminal paper [58] appeared. They used extensive extinction data about 3500 families of marine animals Sepkoski had collected for years. After scrutinizing the data, only 567 families were selected for which the data were considered as the most reliable. The extinction rates of these families plotted versus the geological time exhibited a puzzling periodicity. Fig. 2 shows Raup and Sepkoski's original data as presented by Muller [59].

The geological time scale accuracy is a rather subtle point [60] and not everybody agrees that the periodicity is statistically significant. But we think that Raup and Sepkoski's analysis should be considered as at least a strong indication of 26-30 Myr periodicity in the extinction data. Especially if you take into account that the same periodicity was confirmed in Sepkoski's later studies of fossil genera [61]. A similar periodicity has been observed in the cratering rate on the Earth [62, 63], in magnetic reversals [64] and in orogenic tectonism [65].

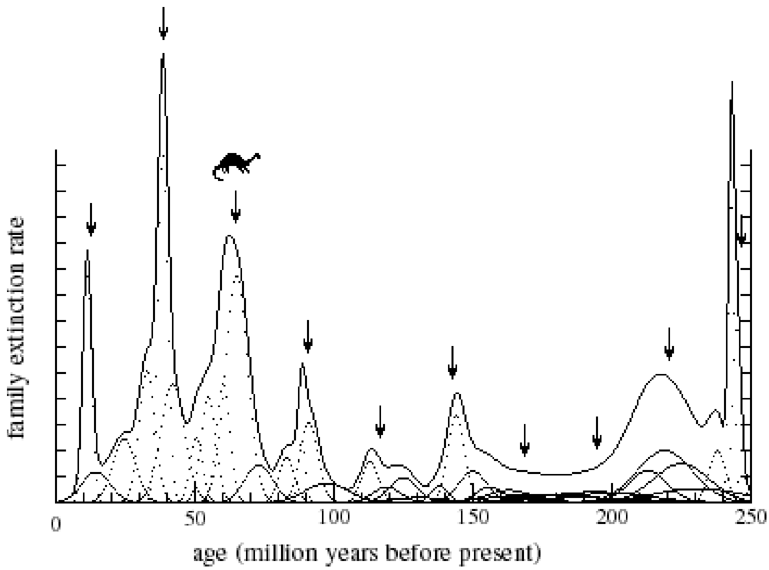


Fig. 2. Extinction rates versus geological time. Each data point is plotted as a Gaussian, with width equal to the uncertainty of the geological age, and area equal to the extinction magnitude.

But if this mysterious periodicity is indeed real, you need some extraordinary explanation for it. Some such explanations were suggested shortly after Raup and Sepkoski's findings. All of them use extraterrestrial causes to explain terrestrial mass extinctions. This is not surprising because only in astronomy one can find clocks with such a large period.

Rampino and Stothers suggested [63] that the Sun's motion perpendicular to the galactic plane can modulate comet fluxes streaming towards the inner solar system, because when the Sun crosses the galactic plane twice in his $\sim$60 Myr period oscillations the probability to meet molecular clouds increases. Of course, it is an interesting fact that the half-period of solar oscillations perpendicular to the galactic plane practically coincides to the mass extinctions period. But at least two obvious drawbacks of this hypothesis can be indicated. First of all, the present amplitude of the solar oscillations perpendicular to the galactic plane is comparable with the scale of molecular clouds height. So it is unlikely these Sun's oscillations to be able to produce any detectable periodicity in encounters with molecular clouds [66]. Besides, the Sun's oscillations in and out of the galactic plane are out of phase with mass extinctions: the Sun is presently just near the galactic plane, whilst we are about half-way between extinctions [67].

Another mechanism, which can lead to periodic comet showers, postulates the existence of yet undiscovered tenth planet (planet X) in the solar system [68]. It is assumed that this planet had swept out a gap in the comet disk beyond the orbit of Neptune during its lifetime. If the orbit of planet X has modest eccentricity and inclination to the ecliptic, it will pass close to the inner and outer edges of the gap twice in its perihelion precession period. And this precession period is expected to be about 56 Myr — nearly twice the extinction period, if the semi-major axis of the orbit is ~ 100 a.u. — big enough to ensure that it is not a simple matter to discover such planet. This is an interesting hypothesis but the question with it is whether the needed gap in the comet distribution around the tenth planet could be maintained [69].

Most solar-type stars have companion(s). Partially based on this observation, Davis *et al.* [67] and independently Whitmire and Jackson [70] suggested that the Sun maybe is no exception and also has a distant companion star. How can this putative solar companion cause periodic comet showers? If its orbital period is $\sim$26 Myr it will have a large semi-major axis $a \approx 8.8 \times 10^4\ a.u. \approx 1.4$ light years according to the Kepler's third law. But even in this case its perihelion $r_{\min} = a(1-e)$, where e stands for the orbital eccentricity, can be of the order of 3×10^4 a.u. if $e \approx 0.7$, sufficiently low to disturb the inner Oort cloud — a comet reservoir containing about 10^{13} comets. Then every perihelion passage of the companion star will induce a cometary shower which after some tens of thousand years will enter the inner solar system and some of them will hit the Earth with high probability. Schematically this is shown in Fig. 3 [71].

The hypothetical solar companion star was named Nemesis, "after the Greek Goddess who relentlessly persecutes the excessively rich, proud and powerful" [67]. This name became the most popular, although the Hindu God of destruction Shiva and his Mother Goddess Kali were argued to be alternatives more suitable to convey dual aspects of mass extinctions [69,72].

Let us take a bit closer look at the Nemesis theory and estimate how many comets are expected to hit the Earth because of the Oort cloud perturbation caused by Nemesis. To do this, we need some model for the distribution of comet orbits in the inner Oort cloud and we take the simplest model [69]: all comets have the same semi-major axis $a = 10^4$ a.u. and their positions and velocities are uniformly distributed in the phase space. Only comets with the perihelion distance $a(1-e) < 1$ a.u. cross the Earth's orbit and for each crossing have some chance to hit the Earth. These comets should have orbital eccentricities $e > 1 - 1\ \text{a.u.}/a = 1 - 10^{-4}$. So the fraction ν of the inner Oort cloud comets which will cross the Earth's orbit twice within 1 Myr, the cometary orbital period for our choice of their semi-major axis, is given by

$$\nu = \int\limits_{0.9999}^{1} f(e)de\,. \tag{11}$$

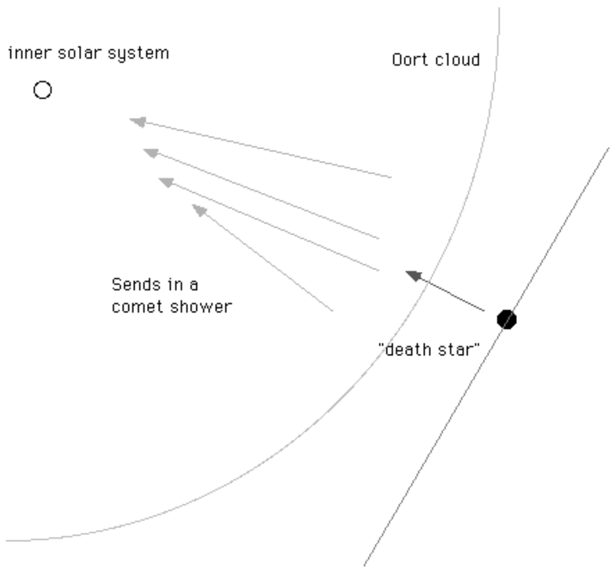


Fig. 3. The companion star induces comet shower while passing near the inner Oort cloud.

Here $f(e)$ is a distribution function for the eccentricity e. Because, for fixed semi-major axis, $1 - e^2 \sim L^2$, L being the orbital angular momentum, the distribution function for e^2 is the same as the distribution function for L^2. The latter can be derived from our supposition about the uniform distribution of the comets in the phase space. But it is possible to guess this distribution function more easily by using the analogy with a highly excited quantum-mechanical hydrogen atom [69]. For highly excited states $L^2 \sim l^2$, where $l \gg 1$ is the total angular momentum quantum number. Let us ask: if one excites a hydrogen atom what is the probability that the quantum number l will lay within the range from l to $l + \Delta l$? Each hydrogen atom level is $(2l + 1)$-fold degenerate. So the desired probability will be proportional to

$$\sum_{l}^{l+\Delta l} (2l+1) \approx \int_{l}^{l+\Delta l} 2l \approx 2l\Delta l \,,$$

where we have assumed $l \gg 1$. Therefore, the distribution function for l is $g(l) = 2l$ in the classical limit $l \gg 1$. This means that l^2 is distributed uniformly, and so does L^2 and hence e^2. But if e^2 is distributed uniformly, the distribution function for the eccentricity will be $f(e) = 2e$ and (11) gives

$$\nu = \int\limits_{1-10^{-4}}^{1} 2e de \approx 2 \times 10^{-4}.$$

The total number of comets in the inner Oort cloud is estimated to be $N = 10^{13}$. Therefore $\nu N \approx 2 \times 10^9$ comets will rush towards the Earth in every 1 Myr. The geometrical cross section of the Earth constitutes 1.8×10^{-9} part of its orbital area. And this number should be even slightly enhanced because of the gravitational focusing (about 1.1-times [69]). Therefore the expected number of comet hits on the Earth's surface is about $2 \times 10^9 \times 1.8 \times 10^{-9} \times 1.1 \times 2 \approx 8$. Here the last factor 2 accounts for the fact that a comet will cross the Earth's orbit twice during its perihelion passage and, therefore, will have two chances to hit the Earth.

This estimate indicates that the Earth would be a very hazardous place, hardly capable to develop any complex forms of life, unless it has some protection against these comet storms. And it is really protected by its faithful safeguards Jupiter and Saturn. Most of the comets crossing Saturn's orbit will be ejected from the solar system after a few orbital period due to gravitational perturbations by Jupiter and Saturn. Because of this effect, the distribution of the Oort cloud comets in the phase space is in fact not uniform: the region corresponding to orbits that enter the inner solar system, the so called "loss cone", is normally empty. Therefore the Earth usually sits secure in the quiet "eye" of the comet storm [67].

Do you realize that we owe our opportunity to attend this conference to Jupiter? I was quite amazed when this thought crossed my mind while preparing these notes. Complex life might be quite rare in the universe [73]. It is not sufficient to find a star like the sun which has a planet like the Earth. You need also to supply respective safeguards.

When Nemesis comes close, it disturbs Oort cloud comets and, as a result, fills the loss cone. In other words, this means that about two billion comets are sent towards the Earth each time Nemeses passes its perihelion. The total number of impacts expected on Earth will be higher than eight – our above estimate. Paradoxically, this is due to effects of Jupiter and Saturn. A small number of comets from the Nemesis induced shower will not be immediately expelled from the solar system by these safeguards but instead perturbed into smaller, frequently returning orbits. This comets will visit the planetary system several times until their final ejection on hyperbolic orbits or disintegration due to a close approach to the Sun. Hence the probability to hit the Earth increases several times, up to order of magnitude [69].

As we see, if the Nemesis is heavy enough to fill the loss cone, its close approaches to the Sun will be catastrophic for creatures like dinosaurs. Smaller creatures, like cockroaches, can possibly survive and enjoy the night sky filled with comets, with several new comets appearing every day. It was shown [69] that if the mass of the Nemesis is not much smaller than 0.1 $M_{\odot}$, the loss cone will be indeed filled by a single perihelion passage of the perilous solar companion for assumed eccentricity $e = 0.7$.

The next obvious question to be answered before acceptance of the Nemesis theory is the stability of such a wide binary system. While orbiting the Sun, Nemesis experiences both slowly changing and rapidly fluctuating perturbations. The former is due to galactic tides and the Coriolis forces (remember that the solar rest frame rotates around the galactic center). The latter is caused by passing field stars and interstellar clouds.

For assumed semi-major axis, the Nemesis is in the region where the Sun's gravity still dominates over the Galaxy field. But due to galactic tides, the orbit oriented parallel to the galactic plane is more stable than orbits at higher galactic latitudes [69, 74, 75]. Moreover, retrograde orbits are more stable because for such orbits Coriolis forces increase stability [75]. Therefore it may be more probable for the Nemesis to be located at low inclinations with respect to the galactic plane. But it is not excluded that present day Nemesis has high inclination, because its orbit is not rigid but subject to various perturbations. So one can imagine that Nemesis started with low inclination and much less wide orbit and random perturbations had lead to its present wide and high galactic latitude orbit, where it can still have several hundred Myr lifetime [69] (according to [75], the lifetime for an orbit perpendicular to the galactic plane is $\sim$500 Myr).

The perturbing effects of passing field stars were studied by extensive numerical calculations [74, 76]. It was shown that the period of "double star clock" fluctuates randomly due to this effect. But the expected drift in orbital period over last 250 Myr (the geological period of interest in a light of Raup and Sepkoski's data) is within a 10 to 20 % – low enough not to spoil periodicities in observable mass extinction data.

The lifetime of 10^3 Myr for the Sun-Nemesis system found in this calculations suggests that it is not possible for the Nemesis to be on such wide and eccentric orbit all the time during solar system existence. So either Nemesis was captured by the Sun relatively recently — the event considered as extremely unlikely [77] because it requires three-body encounters or very close encounters to allow a tidal dissipation of the excessive energy, or its orbit was much more tight at early years of solar system and random-walked to its present position. In the latter case one can expect higher bombardment rate in the past. And it is known that at least in the period between 4.5 and 3 Gyr the bombardment rate was indeed very high. It is believed that one such collision of a planetary size object with the Earth lead to the formation of the Moon. Intriguingly, a moon of right size and at right position appears to be one more ingredient for complex life to develop on the Earth's surface [73], because it minimizes changes in the Earth's tilt, ensuring climate stability.

One more important question was successfully settled by these numerical calculations. In principle, some perturbation can force Nemesis to enter into the planetary system and cause "a catastrophe of truly cosmogonical proportions" [76]. Fortunately, this fatal event turned out to have a very low probability and hence the planetary system can survive the presence of distant solar companion [74, 76].

The effects of interstellar clouds are the most uncertain. Opinions about the fate of Sun-Nemesis system here change from extreme pessimistic [78] to extreme optimistic [79]. The truth should lay somewhere in the middle between these two extremes. Unlike a field star, a single close encounter with a giant molecular cloud can instantly disrupt a wide binary. But in contrast to the stellar neighborhood of the Sun, both the distribution and internal structure of the interstellar clouds are poorly known near the Sun [69]. Disruptive effects of interstellar clouds were investigated by Hut and Tremaine [80]. Their analysis indicate that the effects of interstellar clouds lead most probably to the lifetime of 10^3 Myr for distant solar companion, comparable to the lifetime caused by stellar perturbations [69]. Therefore interstellar clouds seem to be also harmless for the Nemesis hypothesis if Nemesis begins its career at much tighter orbit than the postulated present orbit.

To summarize, there are some indications of 26–30 Myr periodicity in mass extinction data and in some other geological phenomena. This periodicity can naturally explained if we assume existence of a distant solar companion star – Nemesis. Its present orbit is not stable enough to ensure such a wide and eccentric orbit all the time since the solar system formation. But if the Nemesis was on a much more tighter orbit in the past and random-walked to its present position due to various perturbations, nothing seems to invalidate the hypothesis. The only drawback of this theory is that Nemesis was never found. And this is the point where mirror world enters the game: you can't expect to discover Nemesis through conventional observations if it is made from some mirror stuff, can you?

But why mirror Nemesis? Is any more serious reason for the God, except to hide Nemesis from us, to choose the mirror option? Maybe there is. While looking at the solar system, an obsessive impression appears that every detail of it was designed to make an emergence of complex life possible [73]. And it took billions of years of evolution for creatures to appear as intelligent as we are. Nemesis, it is believed, had played an important role in this process, periodically punctuating evolution. Therefore you need the Nemesis to orbit for ages. As we have mentioned earlier, the best way to do this is to place the Nemesis orbit at lower galactic latitudes to minimize disruptive effects of galactic tides and hence increase the orbit stability. But if Nemesis is made from the ordinary matter and was formed from the same nebula as the rest of the solar system, you expect the Nemesis orbit to be in the ecliptic plane — at high galactic latitudes. On the contrary, if the solar system was formed from a nebula of mixed mirrority (the possibility of such nebula was considered in [81]), a priori there is no reason the mirror part of the nebula to have the same angular momentum direction as the ordinary part. So for mirror Nemesis it is natural just to be formed in a plane different from the ecliptic.

Of course, the above given arguments are not completely rigorous. But who knows, maybe the answer to the question "what killed the dinosaurs?" really sounds like this: Nemesis, the mirror matter sun.

8. Conclusions

The mirror Nemesis hypothesis emerged almost as a joke during our e-mail discussions with Robert Foot. After some thought we found no reason why this hypothesis, although somewhat extravagant, might not be true [82]. As a result, the dinosaur theme, which I originally intended to introduce for just to make presentation more vivid, quickly became one of the central motives of this talk, and you have the story presented above. I hope you enjoyed it regardless whether dinosaurs were really eyewitnesses of the mirror world or not.

I consider the possibility to restore the equivalence between left and right through the mirror world as very attractive. Theories with extra spatial dimensions, and M-theory in particular, can easily produce various "shadow worlds" which are however not necessarily parity invariant (this refers to the $E_8 \times E_8$ model also, mentioned earlier), but some of them might be, so realizing the mirror world scenario. Maybe, it is even possible to have a mirror world without mirror particles. M-theory nonorientable compactifications, suggested so far [83], do not lead to the realistic model, as I can judge. But it will be very interesting to find a realistic example and show that the parity noninvariance of our world indicates to its nonorientable topology and is only local phenomenon.

"In the Soviet scientific society the scientists had one freedom that scientists in the West lacked and still lack (perhaps the only real freedom that Eastern scientists had), and that was to spend time also on esoteric questions. They did not have to be scrutinized by funding agencies every now and then" [84]. The Soviet Union disappeared and so did this freedom. You can consider this paper, if you like, as a nostalgia for this kind of freedom, enabling one to escape bonds of the stiff pragmatic logic.

Although, as I became aware while preparing these notes, historically I owe my chance to attend this beautiful place and conference to Jupiter, the Moon and Nemesis, all their efforts would be in vain without professor Zurab Berezhiani. I thank him very much for giving me a possibility to attend the Gran Sasso Summer Institute, and for his kind hospitality during the conference. I also thank Denis Comelli, Francesco Villante and Anna Rossi for their help at Ferrara and Gran Sasso.

I'm indebted to Sergei Blinnikov for encouragement and for indicating the Hubble–Hipparchos controversy.

The content of this talk would be very different without fruitful discussions with Robert Foot, which I acknowledge with gratitude.

I thank Piet Hut for sending me reprints of his articles, which were heavily used in these notes.

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