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The Mysterius Fate of Stars (*Past, Present and Future of the Universe*)

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Abstract

The research on the collapse of stars, due to Gravity, after the depletion of the fusion fuel, engaged a number of famous guys as Eddington, Chandrasekhar, Schwarzschild and Oppenheimer in the years around 1910-1050. During this period, Einstein was writing his field equation of general relativity (1923), Fermi, in a famous letter to Pauli, proposed the neutrino in beta decay theory (1930), Chadwick found the neutron, that granted him the Nobel price (1935) and Hubble (1929) proved that the Universe was expanding. As a result of that golden age, we remain with a lot of unsolved questions, due to the poor knowledge of the nature of the strong Nuclear Interaction of Gravity that controls the whole Universe. We have made an investigation on the nature of nuclear bond and gravitational attraction on the basis of available data and as a follow-up of Fermi famous research on Neutrino. Using this background, we hope to be able to explain or give some light to the evolution of stars, to the strange objects and phenomena captured or perceived by astronomers in the sky and speculated by theoretical physicists.

Keywords

Physics, Gravity, Astrophysics, Grand Unified Theory, Nuclear Bond, Neutrino, Particle Physics

1. Introduction

In 1924, Eddington theorized that stars would collapse to dwarfs and the gravitational pressure that was squeezing a dwarf might strip some of the electrons off the protons. The atoms would then lose their boundaries and might be squeezed together into a small, dense package called white dwarf.

At that time, Chandrasekhar was travelling on a boat from India to England and, being a young mathematician, spent his travel time to develop a theory that fixed a limit to the mass of collapsing stars.

This maximum limit is known as the Chandrasekhar critical mass and equals about 1.4 times the mass of the Sun. Any dwarf more massive than this number cannot be stable.

Chandrasekhar's result deeply disturbed Eddington who began to attach personally this theory: massive stars were destined to collapse gravitationally into oblivion and black holes had to disappear.

On the other hand, Eddington promoted Einstein work on gravitation, on his general theory of relativity and proved the bending of light by Gravity.

Einstein, however, did not believe that relativity could solve the problem of computing white dwarfs and black holes and when, in 1916, a German astronomer Karl Schwarzschild came up with a solution, he showed his disagreement with this approach because the calculations did neglect singularities popping around the Chandrasekhar radius.

To make his point in 1939, Einstein focused [1] on a collection of small particles moving in circular orbits under the influence of one another's gravitation. He then asked whether such a configuration could collapse under its own gravity into a stable star with a mass equal or greater than Schwarzschild limit. The answer was negative or, in other words, he sustained that black holes cannot exist.

In spite of this, the curious thing is that Einstein was considered to be the father of black holes.

The problems with Einstein gravitational field equation [2] continued: when Einstein learned of Hubble's redshifts, he immediately realized that the expansion predicted by general relativity must be real, and in older life, he said that changing his equations, adding a cosmological constant, was "the biggest blunder of his life".

We know that the Universe, not only is expanding, but the expansion is accelerating, a feature never explained and justified with the existence of a fictitious unknown entity named *obscure energy*, responsible *for* slowing down gravity; contemporarily, an *obscure matter* has been postulated to aid the motion of the Galaxy, a function attributed by others to black holes: the center of the galaxy was identified as the perfect location of black holes.

During these years, Oppenheimer and his students in California were investigating a new theory of black holes and when British experimental physicist, James Chadwick, found the neutron, the neutral component of the atomic nucleus, the discussion shifted towards the neutron stars.

Neutron stars have been thought as a physical alternative to the unknown black holes, but unfortunately, it is well known that the half-life of neutron is fifteen minutes and neutrons will be readily converted to protons.

The Second World War ended the discussion with Oppenheimer engaged in Manhattan Project in which Chadwick was deeply involved, together with Fermi, escaping from Europe just in occasion of his Nobel price (1935).

Fermi did excel both in theoretical and experimental physics and, differently from the habits of the moment, found his extraordinary research activity on observation of nature and on using mathematics for the interpretation of experiments, in a perfect Galilean mode.

Together with his selected team of researchers in Rome, he obtained new data for the nuclei of the periodic table, and proposed a way protons and neutrons interact in the nuclei, transforming the one in the other, contemporarily with the emission of an electron and a neutrino in beta decay and studied the nuclear neutron induced reactions that became the basis for the realization of the first fission chain reactor in Chicago (1942).

The findings of Fermi [3] gave a major improvement to the knowledge of the nuclear atom and were of great benefit to the progress of mankind; the influence of his findings on Oppenheimer was relevant for the development of theory of degenerative gasses.

Therefore, living for a moment the unknowns, we remain with white dwarfs, that are described as dense mass, comparable to core of the Sun, while their volume is comparable to Earth, whose existence has been found by astronomers.

Following Wikipedia [4], *white dwarfs are thought to be the final evolutionary state of stars whose mass is not high enough to become a neutron star or black hole. This includes over* 97% *of the stars in the Milky Way. After the hydrogen-fusing period of a main-sequence star of low or medium mass ends, such a star will expand to a red giant during which it fuses helium to carbon and oxygen in its core by the triple-alpha process. If a red giant has insufficient mass to generate the core temperatures required to fuse carbon (around* 1 *billion K), an inert mass of carbon and oxygen will build up at its center. After such a star sheds its outer layers and forms a planetary nebula, it will leave behind a core, which is the remnant white dwarf. Usually, white dwarfs are composed of carbon and oxygen (CO white dwarf). If the mass of the progenitor is between* 8 *and* 10.5 *solar masses* ($M_\odot$), *the core temperature will be sufficient to fuse carbon but not neon, in which case an oxygen-neon-magnesium (Oneg or ONe) white dwarf may form. Stars of very low mass will be unable to fuse helium; hence, a helium white dwarf may form by mass loss in binary systems.*

The curious thing is that white dwarfs are supposed very hot when they form, but because they have no source of energy, they will gradually cool as they radiate their energy away and the cooling time may be longer than the estimated age of the Universe. This age is thought to be the time elapsed from the Big Bang and may be estimated at 13.729 billion years from the inverse of Hubble parameter Hb = 69 km/s/Mpc, which is a measure of the expansion of the Universe.

All these cosmological theories are based on a bundle of measurements made in the sky on the life of stars and on the cosmic microwave background, but ignore the main protagonist that is the nuclear atom, the strong nuclear interaction and the weak gravitational field, which is the basic motor of the Universe and the origin of all the unknowns encountered and factiously solved with some science fiction.

To find the unknowns, it has been thought to escape from theory, provoking Nature in extreme condition with the building of large colliders for high energy experiments and of fantastic underground neutrino detectors for measuring and controlling this elusive particle. The idea was to get information on the cross-section of nuclear reactions and possibly on the nature of Gravity, still lacking in the Standard Model of Particles: the building of Genevra large accelerator (one of the world's most expensive and complex experimental facilities) was devoted to capturing Highs' boson, necessary to validate the Standard Model of Particles through the mechanism of mass generation.

On the other hand, the neutrino detectors, like Gran Sasso facility, are used to investigate the nuclear reactions active in the Sun, producing *specific neutrino*.

I have not the experience to comment on the result of these findings; I only know that, when I suggested the neutrino faster (1E−04) than light [5], the idea was readily captured and a neutrino beam was sent from Geneva to Gran Sasso: the experiment failed, because the instruments for measuring the neutrino speed had some problems.

I will follow with interest the *traces* of Higgs boson, waiting for the results of the experiments underway in these large powerful facilities.

In the meantime, I will bring some light on the unknowns, standing on available experimental data and using my approach to Gravity and to the nuclear bond, as a follow-up of the work of Enrico Fermi.

But before, for the benefit of the novel readers, let us see how we can reboil existing data in the kettle of science.

2. The Misleading Gravity and Nuclear Interactions

The use of Gravity to explain physical phenomena, without knowing its nature, caused in the past several headaches and represented the true obstacle for the development of science.

Newton himself was looking for the physical meaning of his Universal Gravitational Law and was surprised that, using Gravity as a *force* in his differential equations of motion, the solution, for a multi-body problem, was so hard.

The mathematical complexity of Einstein Field Equations did not make the solution easier and represent an example of the difference between reality and its mathematical formulation.

Gravity is not a force, could be represented as a field, but is the result of the nuclear interactions that are the other face of the same coin.

As suggested by Fermi, for beta decay, protons p and neutrons n continuously transform with the following reaction scheme:

$$\begin{array}{lll} \beta^- \text{ emission} & n \xleftrightarrow{k_1} p + \beta^- + \nu & \\ \beta^+ \text{ emission} & p \xleftrightarrow{k_2} n + \beta^+ + \nu & (1) \\ \text{Orbital electron capture} & p + \beta^- \xleftrightarrow{k_3} n + \nu & \end{array}$$

A neutrino ν is produced and the electron-positron annihilate, yielding two γ photons having energy of 0.511 Mev each, equal to the rest energy of an electron.

$$\beta^- + \beta^+ = 2\gamma \tag{2}$$

We have assumed [6] [7] that these reactions are valid for all nuclides, stable and unstable, and that only proton-neutron interactions exist, contrarily to the common opinion that considers proton-proton, neutron-neutron and neutron-proton the same way.

These interactions are dynamic and represent the energy lost by the nucleus at its formation from protons and neutrons to make the nucleus stable during the allowed n-p transformations.

For example, ^{4}He has six possible non-repeated transformations (**Figure 1**) with14 dynamic bonds (solid lines) and, given bond energy twice the annihilation (2), has a total bonding energy of 14 * 2044 Mev, in good agreement with the mass defect.

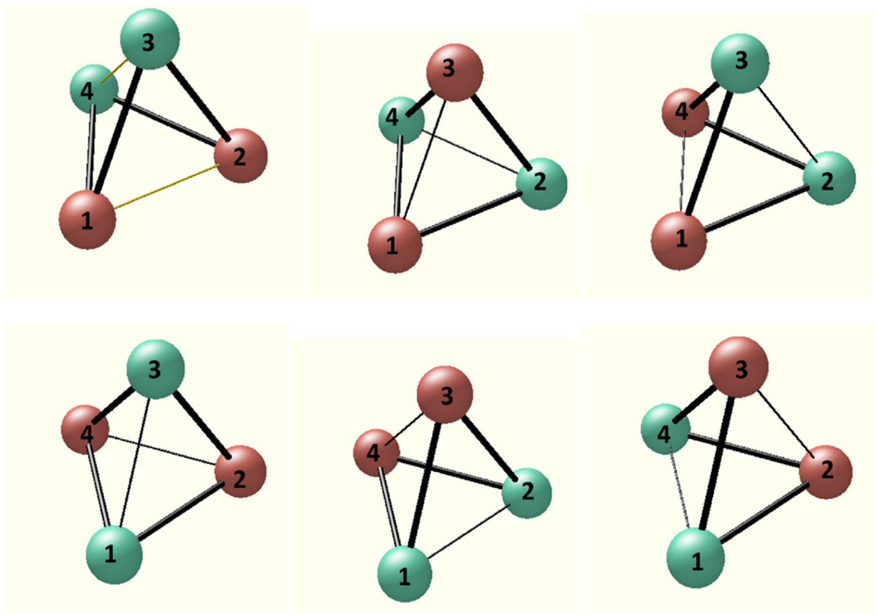

Figure 1. Dynamic transformations and p-n bonds in ^{4}He.

Bonds and bond energy of ^{4}He cannot be explained with traditional theory similarly to ^{2}H, ^{3}H and in general for all light nuclides.

Paper [8] reports the detailed rebuilding of lighter nuclides up to ^{20}Ne, confirming the value twice the electron-positron annihilation energy for both light and heavy nuclides.

This solves the problem of the anomalous behavior of lighter nuclides and provides a general rule for computing the bonding energy and the number of dynamic bonds for all 1812 known nuclides as represented in **Figure 2**.

However, following the dance of proton and neutron and the emission of electrons and positrons, we have not forgotten the flux of neutrino that is free to propagate in the space: electrons and positrons can be emitted if the element is beta active, annihilate or return to the atom if the nuclide is stable.

Given the half-life of neutron, the n-p distribution data for all nuclides (**Figure 3**) give us the possibility to compute the constants of nuclear reactions (2).

We have found for k_1, k_2 and k_3 the following values:

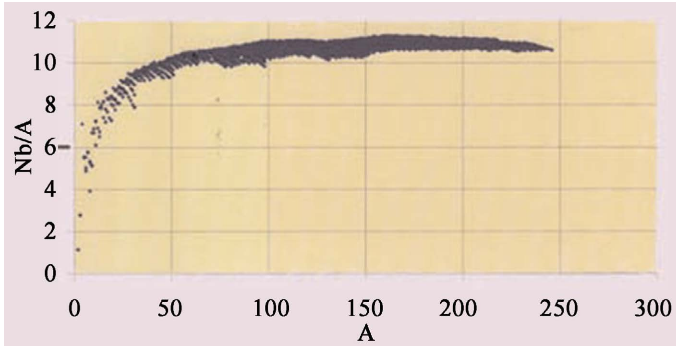

Figure 2. Number of dynamic bonds for stable and unstable nuclides in function of atomic number A under the hypothesis of 2044 Mev bond energy.

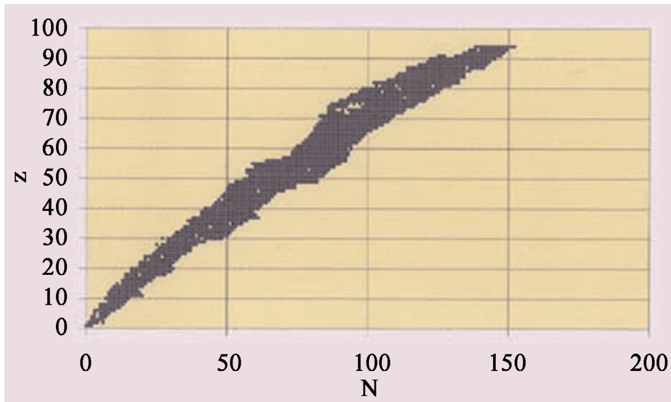

Figure 3. Proton Z and neutron N distribution for all nuclides.

$$k_1 = 0.0009625,\ k_2 = 4.71554\text{E}-06,\ k_3 = 0.00105382 \quad (3)$$

The computation of neutron N and proton Z oscillations, for single nuclides, $\mathrm{d}N/\mathrm{d}t = -\mathrm{d}Z/\mathrm{d}t = k_1N - k_2Z - k_3Z^2$, yields negative values for β^- emitters and positive ones for β^+ emitters, the higher values corresponding to most active emitters: the precision for representing n-p (N-Z) distribution of nuclides present in our universe is so high that authorizes us to consider these constants k as the primary universal ones.

We use these constants to compute the rate of emitted neutrino Foi/ai, per gram and second for all known radioactive and stable nuclides with ni neutrons, pi protons and atomic mass ai (g):

$$Foi = \left(\frac{\mathrm{d}\nu i}{\mathrm{d}t}\right)\Big/ai = \frac{+k_1ni + k_2pi^2 + k_3pi}{ai} \quad (4)$$

The mean value *Fo,* over all existing ***no*** elements, can be easily computed:

$$Fo = \sum_1^{no} Foi/no \quad (5)$$

We discover that it is almost constant for all nuclides with a mean value of *Fo* = 6.668E+20 neutrino per gram per second and this value does not significantly change from light to heavy nuclides with the higher defects for the first elements of the periodic table (**Figure 4**).

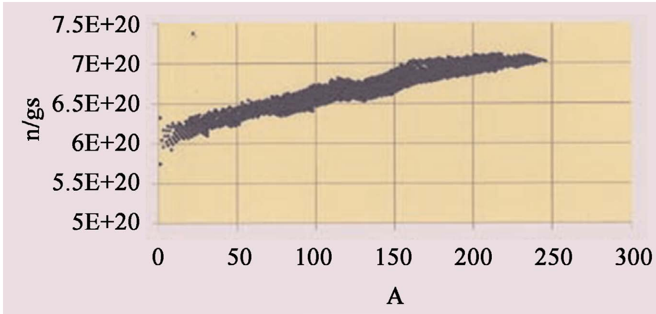

Figure 4. Neutrino flux Foi (neutrino per gram and second) for existing nuclides.

For the neutrino, we assume a temperature of 2.0362˚K a wavelength λ of 0.14232c m, an energy 1.38557E−15 erg or 8.71E−04 ev and an equivalent mass μ = 1.55277E−36 g, that is a particle at a temperature lower than that measured in the universe of 2.725˚K for Cosmic Microwave Background.

The neutrino, with mass μ and speed of light c, are emitted from a body M_1 radially with the inverse square law of distance, cross a receiving body M_2, without interactions and in particular freely cross the nucleons of the body having mass m_n and radius r_n; they sum up with the neutrino emitted by the nucleons of M_2, originating a push of M_2 toward the emitter M_1.

We can therefore write the Newton universal gravitational law in terms of nuclear parameters as follows:

$$F = \left(Fo\mu c r_n^2 / 4m_n\right) M_1 M_2 / R^2 = GM_1 M_2 / R^2 \tag{6}$$

The Gauss constant G can be computed from the neutrino flux Fo:

$$G = Fo\mu c r_n^2 / 4m_n = 1\text{E} - 28Fo \tag{7}$$

This strictly relates gravitation to intrinsic properties of matter and is not surprising, because gravity is a property of matter and more specifically of nuclei.

We can therefore consider the neutrino as the boson of Gravity and relate Fo to Newton gravitational constant G.

In other words, the same mechanism that provides a way to define the nuclear bond and allows the calculation of the nuclear bond energy, explains in a quantitative way the flux of neutrino and hence Gravity.

Newton obviously used a constant value of G for computing the mass of the Earth, the Sun and other planets, but we know (**Figure 4**) that the flux of neutrino is somehow lower for lighter nuclides and in particular for stars and gaseous planets.

Therefore, if the flux computed with G is correct, we have to increase the estimated mass of Sun and gaseous Planets as discussed in Paper [9].

If Newton was lucky with Fo constant and consequently with G constant, we now know that the Universal Gravitational Law is a good approximated model describing real word.

The nature of Gravity and of the strong nuclear interaction is clear, even if it may appear too simple for people engaged in complex formulations with partial differential equations, but data are there and it is surprising that some curious boy did not pay some care to them, using elementary sums and subtractions.

Everybody standing on Earth feels the pressure, from head to feet, of neutrino crossing his body and may think that this may not change his life: this is not true if we think to climate changes, to Earth quakes [10], and other disruptive phenomena or milder effects, induced by the Moon, like tides, growth of plants and life cycles.

For those that are observing the evolution of the sky, the future of the Universe is going to change.

3. The Nuclear Atom Changes Our View of the Universe

When Newton tried to join his attraction gravitational *force* to his equations of motion, incurred in the famous three body problem that, in spite the best mathematicians of the time, remains on the table even today [11].

Einstein thought to have solved the problem of Gravity with his field equation that originates from Navier Stokes for fluid-dynamics and from Maxwell, for the electromagnetic field: he claimed to have unified all these, together with Gravity, in only one set of equations [2].

Unfortunately, Nature seems to dislike mathematics, especially stiff differential equations with boundary constraints and everyone has experienced the difficulty and the impossibility to use these mathematical monuments of science for real problems.

Nature takes it easier, with a number of bodies emitting neutrino and combining the neutrino fluxes in the space to yield the true physical gravitational field that acts on the individual bodies to cause motion [11].

This is the work that the Sun makes to hold the planets in their orbits and, doing this, he loses some of his mass: most of the neutrino flux is lost in the space.

Nature is dissipative and Gravity is the most entropy increasing phenomena present in the Universe in its past and future life.

It is no mystery that the Earth, every year, gains some fraction of second, revolving around the Sun, and that somebody in secret, every year, adjusts the World clock; but nobody says that this is mainly due to the loss of weight of the Sun due to the neutrino release [12].

If this happens at small scale of the planetary system it is no surprise that the Galaxies move apart expanding the Universe and accelerating the expansion: celestial bodies lose matter and therefore the grip of gravity continuously reduces.

It is not necessary to correct Newton equation or hypothesize the existence of an unknown *dark energy*, because Gravity does all by itself.

On the opposite, the mass of the solid bodies present in the universe is contracting and the density of invisible neutrino in the void space is increasing.

All this may excite the fantasy of scientists on the origin, on the idea of the Big Bang and on the future of the Universe.

To be egoistically concrete, let's focus on what might have happened and what will happen to our Sun. This theme, due to the importance for our life, has been extensively treated by papers, news media and books among which we cite the famous dated book of Gamov [13].

It is believed that the Sun formed about 4.6 billion years ago from the collapse of part of a giant molecular cloud that consisted mostly of hydrogen and helium and is about halfway through its main-sequence stage, during which nuclear fusion reactions in its core fuse hydrogen into helium and will remain in this steady stage for additional 46 billion years.

After that period, it is thought that it will become hotter and expand into a red giant, incorporating the rocky planets, during an additional billion years' time.

The final stage will be ejecting half of its mass into a planetary nebula and the naked core becoming a white dwarf that will survive for trillions of years before fading to a hypothetical super-dense black dwarf.

The Sun today has a mass computed by Newton Mo = 1.9885E+33 g with a flux of neutrino Fo = 6.668E+20 neutrino per second and gram; the mass might be larger as described in [9] but we maintain this figure in line with the tradition.

The major part of the mass, approximately 70%, is hydrogen and the remaining Helium.

The total flux of neutrino from the Sun will be Fn = 2.0589E+18 g/s.

On the other hand, the Sun, burning Hydrogen, loses energy by radiation that is estimated 3.8279E+26 joule/s and the equivalent mass of Fr = 4.2593E+12 g/s, that includes some neutrino and the solar wind.

The Sun uses the major part of its energy for controlling the orbits of the planet and only a small fraction to heat them up.

However, during its life, some dramatic incidents may or may have been occurred, like that detected in 2019 for Proxima Centauri, the nearest star to the Sun and host to a number of exoplanets that were selected as potentially habitable.

The Earth has experienced similar events with milder effects, due to the distance from the Sun and to the protection of his strong magnetic field.

Venus and Mars are more vulnerable and may be that is why they lost surface water and some atmosphere and they have no life.

The extinction of dinosaurs, 64 million years ago, has been attributed to a meteorite combined with an intense volcano activity and a climate change, but the direct action of the Sun may better justify the disappearance of the species in all continents.

Forgetting the dramatic billion years of formation of the Sun, probably as a giant star from a giant nebula, we try to concentrate to the 64 million years, of supposed quite existence, after the dinosaurs' extinction, before and after our present life.

The rate of emission of matter due to gravity is K_m = 1.0354E−15 g/g·s, while the mass lost with light is Kr = 2.1419E−21 g/g·s: therefore, we can neglect radiation, even if the Sun was, in the period, some thousand time larger.

The mass of the Sun increases and decreases exponentially before and after our time:

$$\frac{Ms}{Mo} = e^{Km(t-to)} \tag{8}$$

At the dinosaurs' time, the Sun and consequently the Earth were 8.0826986E+00 times more massive and after the future 64 million years will become 1.2372106E−01 lighter.

These variations might appear enormous but are imperceptible from the point of view of Homo Sapiens that has a living time plus or minus 100,000 years from now, as shown in Table 1.

In our short life and in that of our ancestors, we have seen the world repeating itself every year without substantial changes: we are aware of the end of our life but we are not prepared to the end of the world because hopefully we will never see it.

We have only feeble signals, as the already cited increase of some fraction of second of the solar year or the expansion of the Universe measured by Hubble, and, lacking a scientific justification, a series of unknown phenomena and facts have been invented, such as the *obscure energy* and *matter*, the black holes and the *Big Bang*.

A similar situation happened in the late '800, when it was believed that the space was filled with an unknown substance called *ether* whose inconsistence

Table 1. The Sun and the Earth in different geological eras (no density changes).

	Actual Era	Dinosaurs' Era	Far Future	Homo Sapiens	Future
	Now	−64 My	+64 My	−100 Ky	100 Ky
Sun					
Mass g	1.989E+33	1.607E+34	2.460E+32	1.995E+33	1.982E+33
Radius cm	6.957E+10	1.396E+11	3.466E+10	6.963E+10	6.948E+10
Surface Gravity cm/s^2	2.740E+04	5.501E+04	1.366E+04	2.744E+04	2.738E+04
Volume cm^2	1.410E+33	1.139E+34	1.744E+32	1.414E+33	1.405E+33
Density g/cm^3	1.411E+00	1.411E+00	1.411E+00	1.411E+00	1.411E+00
Earth					
Mass g	5.972E+27	4.827E+28	7.389E+26	5.972E+27	5.953E+27
Radius cm	6.371E+08	1.278E+09	3.174E+08	6.370E+08	6.363E+08
Surface Gravity cm/s^2	9.811E+02	1.970E+03	4.891E+02	9.815E+02	9.805E+02
Volume cm^2	1.083E+27	8.751E+27	1.339E+26	1.083E+27	1.079E+27
Density g/cm^3	5.516E+00	5.516E+00	5.516E+00	5.516E+00	5.516E+00

was proved by Michelson and Morley [14], opening the way to Einstein speed of light in vacuum and search for Gravity.

Now, we see that Gravity not only does the job of building and maintain the Universe, but also does the dirty work of destroying it.

May be Chandrasekhar was right in his dispute with Eddington, because Gravity is very efficient to destroy the small number of giant stars observed in the Universe, black holes included.

A special citation is merited by the unfortunate dinosaurs, whose massive bodies and bones had to suffer a surface Gravity twice the actual one and to the unknown species that will populate the Earth in the far future with a Gravity similar to that of the Moon.

We leave our familiar courtyard, the Solar System, and consider massive bodies, weighting some hundred times the mass of the Sun and having a life a fraction of the 13 billion 729 million years life of the Universe.

These bodies might be giant stars or even the notorious black holes that Eddington claimed to be their last form of life.

After 64 million years, the dinosaurs' time, the mass will reduce to 0.12 times that is a mass 100 times the Sun will result only 12 times and the final result might be a Chandrasekhar white dwarf.

After an additional time of 6.4 billion years, the age of the Sun, the reduction will be 1.7553422E−91 and using the birth of the Universe time, the killing action of gravity arrives at the fantastic figure of 2.0652636E−195.

We can therefore define the end of the Universe as the time when existing matter will be converted by gravity and evaporated into a sea of neutrino, provided the existing matter is not infinite.

4. Concluding Remarks

Ever since Gravity has been considered as an aggregating force, governed by Newton Universal Gravitational Law: it is invoked to justify the spherical shape of celestial bodies and their orbital motion and is claimed to be the cause of squeezing matter in the center of the stars, activating the fusion reactions and enlightening the firmament.

Einstein believed that *nature is simple*, but disavowed himself, spending ten years building his monumental mathematical Gravitational Field Equations; he originally believed the Universe to be in a steady state, but his famous curiosity rushed him to join Hubble at Mount Wilson to ascertain the expansion of the Universe.

Now, we know that, in the long times and in the large spaces, Gravity is the most disruptive energy of the Universe, superior, for the effects, even to the sister strong nuclear energy that is burning the stars.

Probably giant stars do not live enough to be transformed in black holes, but the actual models of stars and in particular, the standard model of the Sun, do not consider the energy dissipated by Gravity and should be revised, together with the computations of the interior of the Planets.

The surprising conclusion of this paper is that the original trillion or billion years have been shortened to some million years and more likely, as far as the life of the stars is concerned and, regarding the life on Earth of human beings, to some hundred thousand years.

We live in a special window of time where Nature, with the exception of catastrophic incidents and wars, seems to have prepared to man for an everlasting life, but Earth, in the long times, is aging faster.

This however does not interfere with the life of human beings, as it does not change the past, the present and the future of *Homo Sapiens*, but our scientific view of the world has to change.

The description of the Sun and of the stars has to include the massive release of neutrino, today forgotten in the standard models of the Sun, the mysterious Hubble expansion should be better explained, and the computation of the motion of celestial bodies and of the galaxy could be improved and what else, given that Gravity influences all phenomena on the Earth and on our life.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Notation

F: Newton attraction force (g·cm/s^2)

G: gauss constant (6.668E−08 cm^3·s^{-2}·g^{-1})

M_1, M_2: masses (g)

Mo, Ms: actual and variable mass of Sun (g)

to, t: actual and variable time

R: distance (cm)

μ: neutrino mass (1.55277E−36 g)

ν: neutrino

γ: annihilation photons

λ: wavelength (cm)

Fo: mean neutrino flux (6.668E+20 υ/g·s)

Foi: neutrino flux of nucleus i (υ/g·s)

m_n: nucleon mass (g)

r_n: nucleon radius (cm)

c: speed of light (cm/s)

n: neutron

N: atomic neutron number

ni: neutrons of nucleus i

p: proton

Z: atomic proton/electron number

A: atomic number

pi: protons of nucleus i

a: atomic mass (g)

ai: atomic mass of nucleus i

no: number of nuclei examined

β^+: positron

β^-: electron

k_1, k_2, k_3: constant (3)

Km: rate of mass emission with neutrino (g/g·s)

Kr: rate of mass emission with radiation (g/g·s)