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THE TEACHING OF EVOLUTION

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1. A NEW VISION FOR SCIENCE EDUCATION

Since a decade and worldwide, the need for a high quality scientific education for all children and youngsters has strongly been advocated, put forward and supported by the scientific community and the Academies of science. While this action is partly caused by the reluctance of the young generation, especially in developed countries, to choose scientific careers, other important motivations do exist. The need to understand scientific reasoning and scientific issues becomes essential for citizens having to make decisions in a democracy facing complex problems; sharing the prodigious adventure of contemporary science and its beauty, and participating in it are a matter of justice [1,2]. In this movement, new curricula, new pedagogies, new training plans and resources for teachers are conceived and shared worldwide. We may observe the beginning of a revolution in scientific education [3,4,36].

A striking aspect of the new proposed policies is summarized under the motto '*science for all*', meaning that more than ever science education should be conceived for all children, beginning as early as elementary or even pre-school [5,6]. Doing so is justified by the cognitive development of children and youngsters, but is also a way to ensure basic scientific knowledge for all, as well as to create an extended potential source of future technicians, engineers and scientists. Here a question immediately arises: while science is undoubtedly universal in its methods and results, science education cannot escape to be inscribed in a great diversity of cultural and possibly religious landscapes, which are all of human value and must be respected. As Prof. Wei Yu was stating, speaking from a Chinese point of view (in [2], p. 159-165), 'it is highly important to maintain cultural identity or diversity in globalization'. How can this be achieved 'without reason losing its universal essence neither the world losing its cultural diversity' (J. Mittelstrass, in [2], p. 256)?

In this context, the subject of evolution appears especially critical, and it is not a surprise that it has been at the focus of many discussions, or even conflicts, in recent years. It therefore deserves special attention, as being potentially the subject of confrontations of science with myths, epics, religions and inherited representations of the natural world in various cultures. Specifying what is legitimate for science to enounce, with its power and its current limitations, and explaining why this legitimacy does exist, appear essential in order to avoid misunderstandings on the very nature of science, and unnecessary conflicts. Such conflicts appear in today's world and, in some cases, invade schools and confront teachers, and sometimes parents, with difficult issues which may greatly hamper the very goal of a sound, urgently needed science education.

2. Evolution, a broad subject

In the context of darwinism or neo-darwinism, the concept of evolution is often understood as the biological process affecting living species on Earth, and their changes with epochs over a time span of approximately 3.5 billions years: this is *biological evolution*. But astrophysical discoveries since about one century have brought up a vision of our universe where the physical and chemical conditions, which sustained the apparition of life on Earth, manifest themselves the emergence of complexity, over a time span which is now rather precisely specified to be 13.7 billions years: this is *cosmic evolution*. The two sets of phenomena are clearly not independent. First, the apparition of life on Earth has been dependent of the initial conditions existing then and resulting from the previous cosmic history. Second, life changes over further times occurred in close coupling with factors related to the Earth's evolution, both internal – such as volcanism or continental drift – and others being external, mostly related to the evolution of the Sun – such as variations of solar luminosity and ultraviolet flux, of the solar magnetic field modulating the cosmic rays flux, hence the mutation rate, of solar wind emission, etc. Factors related to Solar system history (exchanges of matter between Earth and meteorites or comets) or even to the nearby interstellar environment, such as supernovae events [7] must also be considered. These coupling mechanisms have operated on a grand scale, the most spectacular example being the transition in the atmospheric composition of the Earth, from an initial, reducing, quasi-equilibrium inert atmosphere to an oxidizing one,

only sustained today by its equilibrium with living organisms. This is *planetary evolution*.

It is quite obvious that our present knowledge of cosmic evolution is still fairly limited to large-scale phenomena, like the apparition of hadrons, atoms, molecules and cosmic dust particles, and the formation of galaxies and stars. Observations of galaxy clusters, gravitational lenses and supernovae as tracers of the universal expansion have even revealed that classical, hadronic matter is only a small fraction (less than 5%) of the total matter-energy content of the known universe: *dark matter* and *dark energy* have been introduced as new, quite mysterious components of reality. Speculations over the existence of parallel universes (*multiverse*) have even broadened the realm of possibilities [8].

On the other hand, while our Solar system was the only one known to contain planets and life, a wealth of discoveries since 1995 has revealed hundreds of such planetary systems, making the existence of Earth-like planets a frequent phenomenon in the universe and indeed questioning the possibility of evolution phenomena leading to various – or unique? – forms of life in these systems.

While biological evolution observes and discusses the process of life on Earth, similar questions may be addressed to cosmic evolution, where the emergence of complexity over time is noticeable and generally agreed upon, starting from a highly undifferentiated and homogeneous universe before the formation of galaxies to reach the present universe. The concept of an *arrow of time* is sustained by the large amount of observational facts which also point to the apparition, in the universe, of complexity and novelties – sometimes qualified as *bifurcations* – not necessarily predictable from the previous state and not contradicting the second principle of thermodynamics. The degree of classical determinism and predictability of the successive steps in complexity encountered by the universe – living organisms, then reasoning humans are the last step we know of – is a difficult issue which has led to a number of different views [9,10]. At one extreme one may find the various expressions of the anthropic principle, with its finalist appearance, while at the other recent efforts are trying to extend the neo-darwinian principles to all phenomena in nature [11]. These are based on the demonstration of a theorem, stating that any physical dissipative structure statistically evolves with time in order to maximize the final dissipation rate of energy (maximal production of entropy, Dewar [12]).

These short considerations on a very complex subject nevertheless indicate that it may not be appropriate to restrain the teaching of evolution, at elementary levels, to the restricted domain of life evolution on Earth. This is indeed the broad perspective view which is briefly presented in the guide produced by the National Academy of Sciences in the United States [13] or by the American Association of Physics Teachers [14]: these documents do not discuss cosmic evolution, but simply observe that the detailed conditions for life emergence on Earth were resulting from previous transformations occurring in the universe.

3. Questions of origin

In all cultures, the question of origins – of the stars and Earth, of matter, of living things, of humans themselves – has produced myths. In these myths, attempts are made to describe with words some imaginary processes where the observed characteristics of the world may be inferred from previous events, caused by all kinds of actors: gods, demiurges, material events. These 'explanations' indeed lack any scientific substance, yet they already contain a certain sense of a necessary causality, combined with a more or less accurate description of natural phenomena through observation. In addition, they indeed contain deep thoughts on the very existence of human beings, which are not immediately relevant for science. At the level of individuals, psychologists have also observed that the question regarding the origin of the self appears as a profound concern during childhood. With the progress of modern science, this haunting question of origins has progressively evolved towards a description of successive transformations occurring in nature, each observed state of organization being traced as the product of an historical process, based on causality and physical properties, where previous conditions lead to a new state – even if a complete description appears at the moment out of reach. Let us simply observe that the fascination of humans for their origins has led large scale research programmes, e.g. at NASA or other agencies, to be placed under this generic designation [15].

On the other hand, philosophers have asked the metaphysical question of *being* (l'*Être*) opposed to the *non-being*, inevitably raising the question of a transition from the latter to the former. This question cannot be decoupled from considering the nature of time, since time appears to belong to the natural world, and statements on the apparition of time are

immediately leading to *aporias*. This was well expressed by Basil of Caesarea: 'The beginning of time is not yet a time, not even the smallest part of a time' [16]. This is probably why it appears so difficult to present, and teach, the scientific description of cosmic evolution: too often there is an implicit understanding which in fact refers to a *creation*, understood as a transition from *non-being* (a metaphysical object of thought) to *being* (an observed fact of nature) – a metaphysical and non-scientific reference indeed. Is it necessary to recall here the popular understanding of the Big-bang model of cosmic evolution as a description of a creation of the world. While Georges Lemaître, whose role in the conception of the *atome primitif* was so decisive, never confused the scientific issue with the Christian vision of creation [17], the view expressed later by Pope Pius XII rather encouraged some kind of concordism [18], even leading to some conceptual oppositions by Fred Hoyle *et al.* to the standard model on the grounds of its supposed metaphysical and undue assumptions. In Western thought, although the distinction between natural processes and a *creatio ex nihilo* was introduced early by Augustine and Tertullian [19], it was often forgotten later on.

After the disputes of vitalism during the XIX century, the origin of life itself on Earth became accepted as a transformation arising from pre-existing physical and chemical conditions, even if the process itself is neither yet understood in detail, nor reproduced in the laboratory. The astronomical discoveries of the last decade have led to the emergence of a new discipline, *astrobiology* (or *bio-astronomy*), which aims at studying the possible observational evidence for the existence of life on extra-solar planets, and the conditions for its emergence. As this new discipline progresses in methodology and tools, a view becomes more substantiated: namely that the physical and chemical conditions, the available time span which made possible the emergence of life on Earth are likely to be encountered in a very large number of planetary system in galaxies. Following Christian de Duve [20], the likelihood of life apparition would then be high. Regarding evolution towards higher forms of complexity and possibly intelligence, the author states: *That extraterrestrial life may evolve in a similar direction is also, by the same token, a realistic possibility* [*ibid.*].

The principle of progressive transformations leading to the emergence of novelty has indeed also been applied by paleontologists to the emergence of man, to describe and understand scientifically the hominisation process, as part of a general evolution of species – the very title of Darwin's work [21]. The complexity of the process, the scarcity of available

evidence to reconstruct an evolution spanning millions of years have not prevented an ever increasing scientific understanding of the *phénomène humain*, to quote here Teilhard de Chardin [22] and quite a solid description of this evolution over the last 5 million years or so.

4. Teaching of evolution

As observed above, scientists also have the responsibility to convey their discoveries to the next generation, not only to perpetuate science, but also to contribute to culture and the enlightenment of all humans. Understanding evolution, cosmic as well as biological, is such an achievement of science that it ought to be shared by all.

Involvement of Academies

Why should one discuss this question of education within the Academies of sciences? Would it not be sufficient to let scientists advise their ministries of education in every country, discuss school curricula, write the necessary books, help train teachers? Is the matter so important that it deserves the interest of an Academy, and especially the Pontifical one?

The central issue which appears in the various discussions on evolution, in the creationism or intelligent design positions is the very understanding of the nature of science, its method, its search for the truth, its meaning in modern culture, since they are questioned or even denied by these movements: this is why Academies are concerned. Referring to the Statutes of the Pontifical Academy, here is clearly an important *epistemological question and issue* (Art.2) where the Academy can *contribute to the exploration of moral, social and spiritual questions* (Art.3). The goal to *'ensure proper education in science for every child in the world'* has now received a clear support from the Academy [1] and from the Pope John-Paul II himself when he said: 'Therefore, because of the ideal of service to truth, [the man of science] feels a special responsibility in relation to the advancement of mankind, not understood in generic or ideal terms, but as the advancement of the whole man and of everything that is authentically human'.[23].

Seizing this challenge and moral obligation to guide education authorities, sixty-eight Academies of sciences, organized in the InterAcademy Panel, published in 2006 a common short Statement [24], which appears to be highly consulted worldwide. In the United States everyone

knows that an intense public debate, related to education issues in primary and secondary schools, has been occurring since several decades, involving mostly Christians. It is analyzed in great detail by Jacques Arnould in his recent book *Dieu versus Darwin* [25], see also [26]. The US National Academy of Sciences published in 2008, after extensive work, a deep revision of an elaborate document explicitely aimed at parents and teachers [27]. The situation in the Muslim world appears more complex [25]. The wide and still ongoing distribution of the *Atlas of Creation* by the Turk Harun Yahya, available today in 11 languages on the Web, appears as the most extreme case of a certain tendency in the Muslim world to interpret the Coran as a scientific scripture and to oppose evolution – considered as a sign of materialistic drift in the Western world. Some Academies there have remained carefully silent on the matter [28]. In Europe, discussions with strongly diverging views were and are still ongoing at the European Council in Strasbourg, regarding the teaching of evolution and possible recommendations to European countries [37].

A pedagogy of science

Christian de Duve has stated with the utmost clarity the heart of the conflict in which many teachers find themselves today regarding the teaching of evolution: 'By making claims that contradict our most intimate convictions […of humankind having a privileged position within some sort of cosmic blueprint designed around and for it…], it is contended, science disqualifies itself as a valid approach to truth' [20].

In the face of this, it is therefore necessary to have a twofold pedagogy: on the one hand, this pedagogy should help discover, understand and accept scientific process as a way of grasping elements of truth; on the other, it ought to respect the search and need to give a sense to the human condition, as well as the expression of this need in various cultures, beliefs and faith. Is this conciliation possible?

Regarding the first point, let us consider the contemporary and active movement of renovation in science education, quoted above [3, also 29,30]. It aims at giving children, youngsters and students an understanding of the very nature of natural science: an ability to question, observe, experiment, hypothetize, deduce, discuss, confirm or disprove from facts, evidence, formulation, prediction and control, establishing progressively fragments of truth and constantly improving their pertinence to reality. This pedagogy communicates science as being a process of knowledge

rather than a collection of imposed theories, or models to be accepted as dogma – eventually opposed to other dogma. Progressive understanding of this process, including what scientists designate by *evidence based*, is the surest way to educate a scientific mind at any level, even elementary. It helps to understand why science operates as a *practical materialism*, methodologically reductionist; it allows to progressively delimit the perimeter of natural science to affirmations, based on evidence, which are testable and refutable; to see that this perimeter is not fixed for ever, but can progressively expand; to understand that on the one hand any question can be asked by science, and on the other that science is modest and does not pretend to reach the ultimate truth, if any.

Regarding the second point, it is important to inscribe the scientific process of discovery in a perspective view, presenting and understanding its historical dimensions. This confers the sense of science as being a human and cultural adventure. Through such a pedagogy, it can be progressively understood how scientific creativity, at any epoch, was also inscribed in the culture, the metaphysics and the global vision of the world where scientists found their inspiration.

A special difficulty arises in what may be called *historical sciences*, namely sciences such as astrophysics, geology, paleontology or evolution science, where models describe past events, which cannot be repeated or submitted to experimental demonstrations (*idiopathic* or *paletiologic* sciences) [31]. While micro-evolution can be observed in the laboratory, this is possible neither for macro-evolution, nor for the early or past universe. There, science may present itself in the mode of *story telling,* as does the East Side Story, popularized by the paleontologist Yves Coppens after the discovery of Lucy [32]. A similar presentation is often made of the early universe, as in the famous book *Three First Minutes* [33] or [34].

It is not entirely surprising that a misunderstanding may then appear about the scientific character of such stories, which becomes confronted with other cultural or popular stories, as are the myths of creation or other poetic descriptions of nature. The central point here is the nature of the proof. In these historical sciences, proof results from a convergence, an internal and external consistency of the proposed description with all pieces of available evidence, including the state of established knowledge in all experimental sciences (physics, chemistry…), and in theories recognized as valid. A new piece of evidence, such as the discovery of dark matter or dark energy in cosmology, may shake the entire edifice, as might the discovery of a new and odd fossil in paleontology or an entirely unexpected func-

tion of a gene in biology. This particular and somewhat subtle epistemology has to be understood by teachers – often very unskilful at this – and properly transfered to students and pupils, a difficult task indeed.

A pedagogy of respect and mutual understanding

Science, being universal in its methods and results, may have an inclination to refute and to challenge any other human experience or vision which does not obey the criteria which regulate its own development. This is *scientism*, an ever present temptation which is at the measure of the grandiose achievements of modern science. It may easily give rise to ideologies which, although non- or anti-religious, have in a recent past been more totalitarian than religions ever were. On the other hand, the goal of religions to embrace and give significance to the totality of human existence can obviously conflict with science – even more when inspired Scriptures, taken literally, provide alternative *stories* of creation or human emergence.

How could then co-exist on the one hand the precious universality of science, on the other the diversity of cultures, the richness provided by the singularity of each human being, the spiritual forces present on Earth? A first point of convergence is indeed *to consider the common sense of humanity, the universality of ethical principles and norms, which are, for instance, expressed in the concepts of human rights and the dignity of the person, as well as in the universality of knowledge, wisdom and science* (Final Statement in [2]). Certainly the teaching of evolution helps to perceive the identity, fragility and common destiny of humanity in the grandiose landscape of the universe today revealed by science [2, *ibid*.].

The emergence of modern science has been on the mode of separation: on the one hand, nature as an object of science, rational, submitted to mathematics, universal; on the other hand, culture as an object of sensitivity and individuality [35]. This dissociation has made possible the development of modern science, but is today challenged by the need to reconcile its technological power and rational mastering of nature with the goals of peace, justice and harmony on a finite Earth. Could a proper scientific teaching of evolution also contribute to such a reconciliation, by pointing out how culture can avoid the catastrophe: a blind natural selection within humanity, operating to the exclusive benefit of the fittest ones?

5. Conclusion: some guidelines?

Here is an attempt to formulate, following previous work on the same goal [13,14,24], some recommendations which may be useful for parents and teachers at primary, secondary and undergraduate levels. Since the author is ignorant of so many aspects of biological evolution, this enumeration should indeed be considered as a modest and grossly incomplete contribution. In a sense, it represents minimal requirements which could be conveyed to teachers, with appropriate examples and illustrations, in order to help them to teach evolution.

Science is a process of knowledge which must be taught, practiced and understood properly, even at elementary levels. Dealing with phenomena and transformations in nature, it is based on evidence, it provides explanations and predictions which are testable and refutable.

Science can also apply rationality and scientific method to events of the past, or events which only happened once. This *historical science* deserves a special epistemological approach, to understand how evidence and proof are established in these cases. This is especially relevant for cosmic or biological evolution.

Biological evolution and the more global frame of cosmic evolution – the latter at least for the epochs where the scientific basis are firmly established – should be taught as solid facts, not as hypothesis.

The history of scientific concepts, their inscription in the culture of the time, should be taught along with the most up-to-date facts and understanding, in order to illustrate the way science has proceeded in the past and still does.

Despite its great appealing and often popular character, the question of *origin* should be treated carefully: namely to avoid a confusion between a transformation occurring from previous physical conditions, and a metaphysical, possibly religious issue.

When answering a question, the aim of science is to build truth, not to propose the final truth, if any. Many questions belonging to science remain open and undecided, but no question should a priori be denied to be asked by science. The perimeter of science is more a question of methodology than legitimacy.

There exist other modes of knowledge than the scientific one, e.g. when dealing with ethical issues. Philosophical, religious, cultural ways of knowing need to be understood and respected, as well as they have to understand and respect science.

A better knowledge and proper understanding of our natural condition on Earth, of its past evolution, its situation in cosmic time and space give humanity the possibility to prepare for the future, to use at best the human wisdom and the universal sense of justice in order to make Earth liveable and sustainable.

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