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Revolutions that made the Earth by Tim Lenton and Andrew Watson, Oxford University Press, Oxford, 2011, pp. xii + 423. Scope: monograph. ISBN 978 0 19 958704 9 (hardback). Level: general reader with a science education.

The Earth differs radically from all other planets that we know of, and the reason is that it harbours life. Life is not just a kind of optional add-on that might or might not be present here; it has very substantially modified the physical properties of the Earth. Thus the evolution of the Earth and the evolution of life are inextricably intertwined. The authors contend that just a few profound revolutions in this interaction have led to the Earth as we know it today – and they ponder about the new (anthropocene) revolution that is currently in progress today and discuss where it may lead.

The authors are both professors at the University of East Anglia. Their book has its origins in discussions over dinner at a conference in Nice in 2002, which is when the authors began to realise that the major transitions in the evolution of life, as enumerated by Eors Szathmáry and John Maynard Smith (SMS transitions), bore an uncanny correspondence to major transitions in the geochemistry of the Earth. It became evident that a meaningful history of the Earth would of necessity have to be a history of the Earth together with the life it harboured. It would also be necessary to work out how the combined system survived each revolution to reach a new quasi-stationary state with the required feedback mechanisms in place to ensure stability. Both authors' PhDs were supervised or part-supervised by James Lovelock so that, in a sense, the similarity to his Gaia hypothesis (that organisms and their physical surroundings are closely integrated to form a single self-regulating complex system, maintaining the conditions for life) is unsurprising. Although they are explicit about their enormous respect for Lovelock and his ideas, they also distance themselves slightly and indicate disagreement with certain aspects of Gaia.

The broad-brush picture of life and how it developed on Earth is already reasonably well established and agreed. Life in the form of prokaryotic cells (bacteria) appears very early on, perhaps 3.5 billion years ago, almost as soon as the Earth was cool enough to accommodate it and the future rocks were able to record its presence. For the next two billion years or so there were only bacteria, albeit of increasing variety. Next, the far more complex eukaryotic cells – those with a nucleus, which provide the building blocks for plants and animals – suddenly appear. Probably a little before this, oxygen photosynthesis evolves, and the growth and activity of cyanobacteria cause a huge increase in oxygen O_2 in the atmosphere. In the upper atmosphere, an ozone O_3 layer is then formed, filtering out the harsh ultraviolet wavelengths from the sunlight and enabling life to colonise dry land. Once there were eukaryotic cells, multicellular organisms appeared with specialised cells, and ever more complicated creatures evolved. Humans are emphatically late-comers on the scene a mere one or two hundred thousand years ago.

The authors have nice ways of describing all this activity and development in their opening chapters, imagining first a sleeper awakening and wondering about their surroundings, and then considering "the view from above" in which a movie of the Earth is played backwards at a hundred million years per minute – enabling the whole history of the Earth to be viewed in a mere three quarers of an hour. They describe the series of changes the external observer would see, including the continents skating across the surface of the globe and eventually agglomerating to form Pangaea, the "snowball earth" episodes, the disappearance of life from the continents, the disappearance of oxygen from the atmosphere, the disappearance of the photosynthetic signature of life from the oceans, and the eventual disintegration of the Earth. Then they imagine replaying the movie forwards again, starting from the solar nebula stage and describing in more detail the formation of the solar system with its Earth, and the subsequent appearance of life on the latter. It is an appealing vision that dramatically summarises what is known, or suspected with high confidence. But, so far, nothing has been said about why things developed like that, or how life came to co-evolve with the Earth in the way it did. But the authors comment that it is life that plays the leading role in each of the revolutions.

What are the critical steps – the difficult (improbable) events that determined the pace of evolution? The authors discuss possible candidates. They start from the SMS transitions: (1) replicating molecules in compartments; (2) genes; (3) genetic code and prokaryotes (bacterial cells); (4) eukaryotes (cells with a nucleus, of which plants and animals are made); (5) sexual reproduction; (6) cell differentiation; (7) society; (8) self-aware observers. They also add an additional transition which they number as (3a) – oxygenic photosynthesis. If there is evidence that a step occurred more than once, then it can be assumed to be "not very difficult". After much discussion and logical argumentation, combining some of the SMS transitions that seem to be relatively easy, the authors settle on four (almost literally) Earth-shaking revolutions:

(a) Inception of life, including the genetic code, prokaryotes, anoxygenic photosynthesis, and leading to a high-methane new stable state.

(b) Oxygen, involving oxygenic photosynthesis, recycling of carbon and nitrogen, and leading to a new stable state with some oxygen in the atmosphere.

(c) Complexity, arising via the eukaryotic cell and its genome, recycling of phosphorus as well as carbon and nitrogen, yielding a stable state atmosphere with an enormously increased oxygen content and low atmospheric CO_2.

(d) Humans, with language, agriculture, civilisation, and use of fossil fuels. Because the revolution has only just started, the new stable state (if any) is not yet known.

The stable states include within themselves gradual step-by-step evolution, but the authors argue that they are distinctly separated from each other because each of them must be preceded by a particularly improbable event.

All of this has obviously to be fitted within the Earth's habitable period. This started about 4.0 billion years ago and will last for another 0.5 billion years (if you are a pessimist) or perhaps 1.5 billion years (optimistic estimate). Of course the end of the habitable period may be brought forward or pushed back by mankind acting collectively, and these estimates make no allowance for that because they just consider the gradual increase in the solar output.

Although not the central theme of the book, the questions being considered bear heavily on the possibility of life elsewhere in the Universe: if any of the critical steps is too improbable, the likelihood of it also having happened somewhere else is correspondingly reduced. The tentative conclusion is that planets that have evolved prokaryotes, and reached stable steady states like that of the early Earth, may be quite common – but those with complex life like we have today are probably extremely rare.

The authors devote a whole chapter to "The origins of us", asking the question of what it is that sets us apart from our hominid ancestors and the rest of the living world. There is no single satisfactory answer, though the formative event was probably the development of natural language with a universal grammar, which underlies our culture and our capacities for abstract thought, planning, and technological innovation. The control of fire is surely significant too, though it seems clear the Homo erectus or another Homo species mastered this before Homo sapiens appeared on the scene. The first Homo sapiens seem to have appeared in East Africa about 200,000 years ago, already with a large cranial capacity.

Yet cultural features like trade, art, and ritual burying of the dead only appeared more recently, around 50,000 years ago. It seems evident that by one or two hundred thousand years ago the brain of Homo sapiens was not much different from the human brain of today, but it remains quite unclear why it should have been so seemingly over-designed for the needs of hunter/gatherers. Why should the brain already have evolved to the state where it was capable, in principle, of constructing the theories of quantum mechanics or general relativity, or appreciating Hamlet or the late Beethoven quartets? All one can guess is that it was the evolution of a general-purpose information-processing system that gave Homo sapiens a special advantage in terms of flexibility in responding to the unexpected – a brain that could be applied to almost anything.

So where do we go next? The anthropocene revolution, where it is one particular species (our own) that is changing the face of the Earth, has only just started. The authors consider two main scenarios by which life and humans might survive to enjoy the rest of the Earth's expected habitable period. The first one they characterise as "retreat", and involves a world with lower energy use, lower material consumption, and reduced population – with the noble long-term aim of sustainability for planet and people. They point out, however, that it is utterly unrealistic, hopelessly contrary to current trends, incompatible with what drives revolutionary change, and ultimately lacking in ambition.

The authors' second scenario is more optimistic and more exciting. They envisage a revolution into a high-energy, high-recycling, world that can support billions of people as part of a fully sustainable biosphere. They point to the huge amount of energy that is potentially available for human use, so that energy requirements as such should not be a problem. Recycling will be an absolute necessity, however, on account of the limited quantities of minerals and other materials essential for technology that are accessible in the Earth's crust. Increased recycling will of course require energy, but there will be plenty available from sustainable (especially solar) and long-term non-carbon (nuclear fission and fusion) sources. It will be necessary for us to wean ourselves off the use of fossil fuels, fast, in order to reduce global warming; it may even become possible and desirable to take active steps to reduce the CO_2 in the atmosphere, and realistic in the high-energy society that they envisage. Could this scenario come about? Well, maybe. It is certainly far more attractive than either retreat or the premature non-habitability of the Earth if it overheats, but a large measure of global agreement between humans will clearly be needed.

This is a big book, with 21 chapters grouped into six parts. It provides a up-to-date cosmic vision of the human situation, how we come to be here, our place in the Universe, and where we may be going. It is hugely detailed, and the arguments given are quantitative and supported by evidence in each case. Where there are uncertainties – and of course there are plenty – these are commented on and, as far as possible, evaluated. The style is lively and attractive (albeit slightly too colloquial for me at times). Although extensive references are provided at the ends of chapters, much of the book is written at a level that anybody why did science subjects at school will be able to understand and enjoy. The first two parts in particular (about one third of the book) range over the whole history of the Earth, and provide a very full picture of what is being presented, but without too much technical detail. What the authors refer to as the "technical heart" of the opus start in Part III and continues to the end of Part V. Here, the material is indeed more technical but no more so than is necessary, and all readers should at least be able to pick up the gist of the arguments being presented. Finally Part VI, evaluating the present and looking to the future, is accessible to almost every intelligent reader.

Revolutions that Made the Earth is a stimulating read. The main thrust of the narrative was already familiar, but much of the detail was new to me, and fascinating, and I had not previously thought about co-evolution of the Earth and life in terms of revolutions. The authors present a broad view that is science, in that it is evidence-based and closely argued, but at the same time potentially popular in terms of its accessibility and the fact that the compellingly important topics addressed are of concern to us all. I feel that they have succeeded quite admirably in their aim of writing "scholarly popular science". Their highly original contribution deserves to be widely read and discussed in the years to come.

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