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Erasmus Lecture
From Mars to the Multiverse

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Unmanned spacecraft have visited the other planets of our Solar System (and some of their moons), beaming back pictures of varied and distinctive worlds – but none propitious for life. However, prospects are far more interesting when we extend our gaze to other stars. Most stars are orbited by retinues of planets. Our home Galaxy contains a billion planets like the Earth. Do some of these have biospheres? Moreover, our Galaxy is one of billions visible with a large telescope – all the aftermath of a cosmic 'big bang' 13.8 billion years ago. More astonishing still, 'our' big bang may not have been the only one. The remarkable advances in recent decades are primarily owed to new engineering and technology. Armchair theory alone doesn't get us far.

1. Introduction

Astronomy is a fundamental science. It's also the grandest of the environmental sciences, and the most universal – indeed the starry sky is the one feature of our environment that's been shared, and wondered at, by all cultures throughout human history. Today, it's an enterprise that involves a huge range of disciplines: mathematics, physics and engineering, of course – but also others.

We want to understand the exotic objects that our telescopes have revealed. But also to understand how the cosmic panorama, of which we're a part, emerged from our universe's hot dense beginning.

The good news is that today is a brilliant time for young researchers. The pace of advance has crescendoed rather than slackened; instrumentation and computer power have improved hugely.

2. Our Solar System, Space Exploration

I'll start with a flashback to Isaac Newton. He must have thought about space travel. Indeed, there is a famous picture, in the English edition of his 'Principia', which depicts the trajectory of cannonballs being fired from a mountaintop. If they are fired fast enough, their paths curve downward no more sharply than the Earth's surface curves away underneath them: the cannonballs go into orbit. This is still the neatest way to teach the concept of orbital flight.

Newton knew that, for a cannonball to achieve an orbital trajectory, its speed must be 25,000 km/hour. But that speed wasn't achieved until 1957 with the launch of Sputnik 1. Four years later, Yuri Gagarin went into orbit. And eight years after that we had the moon landings. The Apollo programme was a heroic episode. But it was all over more than 40 years ago – you've got to be middle-aged to remember when men walked on the Moon; it's ancient history to the younger generation. If the momentum had been maintained there would be footprints on Mars by now. But actually people have done no more than circle the Earth in low orbit – more recently, in the International Space Station.

But space technology has burgeoned – for communication, environmental monitoring, satnavs and so forth. We depend on it every day. And for astronomers it's revealed the far-infrared, the UV, X-ray and gamma-ray sky.

Unmanned probes to other planets have beamed back pictures of varied and distinctive worlds. The most recent has been ESA's Rosetta comet mission, which landed a small probe on the comet itself, to check, for instance, if isotopic ratios in the cometary ice are the same as in the Earth's water – crucial for deciding where that water came from. NASA's 'New Horizons' probe has passed Pluto, and is now heading into the Kuiper Belt.

Rosetta was launched more than 10 years ago; its design was frozen 5 years before that. Its robotic technology dates from the 1990s – that's the greatest frustration for the team that's been dedicated to it for so long, because present-day designs would have far greater capabilities.

I hope that, during this century, the entire solar system will be explored and mapped by flotillas of tiny robotic craft. And, on a larger scale, robotic fabricators may build vast lightweight structures floating in space (solar energy collectors, for instance), perhaps mining raw materials from asteroids or the Moon.

But will people follow them? Robotic advances will erode the practical case for human spaceflight. Nonetheless, I hope people will follow the robots, although it will be as risk-seeking adventurers rather than for practical goals. The most promising developments are spearheaded by private companies. For instance, SpaceX, led by Elon Musk, who also makes Tesla electric cars, has launched unmanned payloads and docked with the Space Station. Musk hopes soon to offer orbital flights to paying customers. Wealthy adventurers are already signing up for a week-long trip round the far side of the Moon – voyaging further from Earth than anyone has been before (but avoiding the greater challenge of a Moon landing and blast-off). I'm told they've sold a ticket for the second flight but not for the first flight. We should surely cheer on these private enterprise efforts in space – they can tolerate higher risks than a western government could impose on publicly funded civilians, and thereby cut costs.

I hope some people now living will walk on Mars – as an adventure, and as a step towards the stars. They may be Chinese. Indeed, if China wishes to assert its superpower status by a 'space spectacular' it would need to aim for Mars. Just going to the Moon, in a re-run of what the US achieved 50 years earlier, would not proclaim parity.

But perhaps the future of manned spaceflight, even to Mars, lies with privately funded adventurers, prepared to participate in a cut-price programme far riskier than any government would countenance when civilians were involved – perhaps even one-way trips. (The phrase 'space tourism' should, however, be avoided. It lulls people into believing that such ventures are routine and low-risk. And if that's the perception, the inevitable accidents will be as traumatic as those of the US Space Shuttle were. Instead, these cut-price ventures must be 'sold' as dangerous sports, or intrepid exploration.)

By 2100, groups of pioneers may have established bases independent from the Earth – on Mars, or maybe on asteroids. But don't ever expect mass emigration from Earth. Nowhere in our Solar System offers an environment even as clement as the Antarctic or the top of Everest. Space doesn't offer an escape from Earth's problems.

What are the long-term hopes for space travel? The most crucial impediment today stems from the intrinsic inefficiency of chemical fuel, and the consequent requirement to carry a weight of fuel far exceeding that of the payload. Launchers will get cheaper when they can be designed to be more fully reusable. But so long as we are dependent on chemical fuels, interplanetary travel will remain a challenge. A space elevator would help. Nuclear power could be transformative. By allowing much higher in-course speeds, it would drastically cut the transit times to Mars or the asteroids (reducing not only astronauts' boredom, but their exposure to damaging radiation).

Another question we're all asked is – is there life out there already? Prospects look bleak in our Solar System, although the discovery of even the most vestigial life-forms – on Mars, or in oceans under the ice of Europa or Enceladus – would be of crucial importance, especially if we could show they had an independent origin. But prospects brighten if we widen our horizons to other stars – far beyond the scale of any probe we can now envisage.

3. Exoplanets and Stars

Perhaps the hottest current topic in astronomy is the realization that many other stars – perhaps even most of them – are orbited by retinues of planets, as the Sun is. The planets aren't detected directly but inferred by precise measurement of their parent star. There are two methods:

(a) If a star is orbited by a planet, then both planet and star move around their centre of mass – the barycentre. The star, being more massive, moves more slowly. But the tiny periodic changes in the star's Doppler effect can be detected by very precise spectroscopy. By now, more than 500 exo-solar planets have been inferred in this way. We can infer their mass, the length of their 'year', and the shape of their orbit. This evidence pertains mainly to 'giant' planets – objects the size of Saturn or Jupiter. Detecting earth-like planets – hundreds of times less massive – is a real challenge. They induce motions of merely centimetres per second in their parent star.

(b) But there's a second technique that works better for smaller planets. A star would dim slightly when a planet was 'in transit' in front of it. An

> earth-like planet transiting a sun-like star causes a fractional dimming, recurring once per orbit, of about one part in 10,000. The Kepler spacecraft pointed steadily at a 7-degree-across area of sky for more than three years – monitoring the brightness of over 150,000 stars, at least twice every hour, with a precision of one part in 100,000. It's already found more than 2000 planets, many no bigger than the Earth. And of course it only detects transits of those whose orbital plane is nearly aligned with our line of sight. We're especially interested in possible 'twins' of our Earth – planets the same size as ours, on orbits with temperatures such that water neither boils nor stays frozen. Some of these have already been identified in the sample, suggesting that there are billions of Earth-like planets in the Galaxy.

The real goal, of course, is to see these planets directly – not just their shadows. But that's hard. To realize just how hard, suppose an alien astronomer with a powerful telescope was viewing the Earth from (say) 30 lightyears away – the distance of a nearby star. Our planet would seem, in Carl Sagan's phrase, a 'pale blue dot', very close to a star (our Sun) that outshines it by many billions: a firefly next to a searchlight. But if it could be detected, even just as a 'dot', several features could be inferred. The shade of blue would be slightly different, depending on whether the Pacific Ocean or the Eurasian land mass was facing them. The alien astronomers could infer the length of our 'day', the seasons, the gross topography, and the climate. By analysing the faint light, they could infer that it had a biosphere.

Within 20 years, the huge E-ELT telescope planned to be built by the European Southern Observatory on a mountain in Chile (where the site has already been levelled) – with a mosaic mirror 39 metres across – will be drawing inferences like this about planets the size of our Earth, orbiting other Sun-like stars. But what most people want to know is: could there be life on them – even intelligent life? Here we're still in the realm of science fiction.

We know too little about how life began on Earth to lay confident odds. What triggered the transition from complex molecules to entities that can metabolize and reproduce? It might have involved a fluke so rare that it happened only once in the entire Galaxy. On the other hand, this crucial transition might have been almost inevitable given the 'right' environment. We just don't know – nor do we know if the DNA/RNA chemistry of terrestrial life is the only possibility, or just one chemical basis among many options that could be realized elsewhere.

Moreover, even if simple life is widespread, we can't assess the odds that it evolves into a complex biosphere. And, even it did, it might anyway be unrecognizably different. I won't hold my breath, but the SETI (Search for Extraterrestrial Intelligence) programme is a worthwhile gamble – because success in the search would carry the momentous message that concepts of logic and physics aren't limited to the hardware in human skulls.

And, by the way, it's too anthropocentric to limit attention to earth-like planets, even though it's prudent strategy to start with them. Science fiction writers have other ideas – balloon-like creatures floating in the dense atmospheres of Jupiter-like planets, swarms of intelligent insects, etc. Perhaps life can flourish even on a planet flung into the frozen darkness of interstellar space, whose main warmth comes from internal radioactivity (the process that heats the Earth's core).

We should also be mindful that seemingly artificial signals could come from super-intelligent (though not necessarily conscious) computers, created by a race of alien beings that had already died out. Indeed, I think this is the most likely possibility. We may learn this century whether biological evolution is unique to our Earth, or whether the entire cosmos teems with life – even with intelligence.

Even if simple life is common, it is a separate question whether it's likely to evolve into anything we might recognize as intelligent or complex. Perhaps the cosmos teems even with complex life; on the other hand, our Earth could be unique among the billions of planets that surely exist. That would be depressing for the searchers. But it would allow us to be less cosmically modest: Earth, though tiny, could be the most complex and interesting entity in the entire Galaxy.

Back now to the physics – far simpler than biology. What has surprised people about the newly discovered planetary systems is their great variety. But the ubiquity of such systems wasn't surprising. We've learnt that stars form, via the contraction of clouds of dusty gas; and if the cloud has any angular momentum, it will rotate faster as it contracts, and spin off a dusty disc around the protostar. In such a disc, gas condenses in the cooler outer parts, while closer in less volatile dust agglomerates into rocks and planets – this should be a generic process in all protostars.

In the remainder of this article, I'll outline how the cosmogonic causal chain has been pushed back further – to the formation of galaxies, stars, atoms, and right back to the first nanosecond of the big bang.

First, what about stars and atoms? We see stars forming, in places such as the Eagle Nebula, 7000 lightyears away. And we see many stars dying – as the Sun will, in around 6 billion years, when it exhausts its hydrogen fuel, blows off its outer layers, and settles down to a quiet demise as a white dwarf.

More massive stars die explosively as supernovae, generally leaving behind a neutron star or black hole. The most famous is the Crab Nebula, the expanding debris from a supernova recorded by oriental astronomers in AD 1054, with, at its centre, a neutron star spinning at 30 revs/second (and these fascinating objects, natural 'laboratories' for the study of extreme physics, could be the topic for a separate presentation).

Supernovae are important for us: if it wasn't for them we wouldn't be here. By the end of a massive star's life, nuclear fusion has led to an onion skin structure – with hotter inner shells processed further up the periodic table. This material is then flung out in the supernova explosion. The debris then mixes into the interstellar medium and recondenses into new stars, orbited by planets.

The concept was developed primarily by Hoyle and his associates. They analysed the specific nuclear reactions involved, and were able to understand how most atoms of the periodic table came to exist and why oxygen and carbon (for instance) are common, whereas gold and uranium are rare.

Our Galaxy is a huge ecological system where gas is being recycled through successive generations of stars. Each of us contains atoms forged in dozens of different stars, spread across the Milky Way, which lived and died more than 4.5 billion years ago, polluting the interstellar cloud in which the Solar System condensed.

4. Beyond Our Galaxy – Cosmic Horizons

Let's now enlarge our spatial horizons to the extragalactic realm. We know that galaxies – some disc-like, resembling our Milky Way or Andromeda, others amorphous 'ellipticals' – are the basic constituents of our expanding universe. But how much can we actually understand about galaxies? Physicists who study particles can probe them, and crash them together in accelerators at CERN. Astronomers can't crash real galaxies together. And galaxies change so slowly that in a human lifetime we only see a snapshot of each. But we can do experiments in a 'virtual universe': computer simulations, incorporating gravity and gas dynamics.

We can redo such simulations, making different assumptions about the mass of stars and gas in each galaxy, and so forth, and see which matches the data best. Importantly, we find, by this method and others, that all galaxies are held together by the gravity not just of what we see. They're embedded in a swarm of particles that are invisible, but which collectively contribute about five times as much mass as the ordinary atom – the dark matter.

And we can test ideas on how galaxies evolve by observing eras when they were young. The Hubble Telescope has been used to study 'deep fields', each encompassing a tiny patch of sky – just a few arc minutes across. You can see hundreds of smudges – these are galaxies, some fully the equal of our own, but they're so far away that their light set out more than 10 billion years ago – they're being viewed when they've recently formed.

But what happened still further back, before there were galaxies? The key evidence here, dating back to Penzias and Wilson 50 years ago, is that intergalactic space isn't completely cold. It's warmed to 3 degrees above absolute zero by weak microwaves, known to have an almost exact black-body spectrum. This is the 'afterglow of creation' – the adiabatically cooled and diluted relic of an era when everything was squeezed hot and dense. It's one of several lines of evidence that have allowed us to firm up the 'hot big bang' model.

The background radiation was last scattered when the temperature was 3000 degrees and the free electrons combined with nuclei to mainly H and He atoms. This was after about 300,000 years of expansion. The He and D abundance was determined by nuclear reactions in the first few minutes, at temperatures of a few billion degrees. More about this later.

But first, let's address an issue that might seem puzzling. Our present complex cosmos manifests a huge range of temperature and density – from blazingly hot stars, to the dark night sky. People sometimes worry about how this intricate complexity emerged from an amorphous fireball. It might seem to violate the second law of thermodynamics, which describes an inexorable tendency for patterns and structure to decay or disperse.

The answer to this seeming paradox lies in the force of gravity. Gravity enhances density contrasts rather than wiping them out. Any patch that starts off slightly denser than average would decelerate more, because it feels extra gravity; its expansion lags further and further behind, until it eventually stops expanding and separates out. Many simulations have been made of parts of a 'virtual universe' – modelling a domain large enough to make thousands of galaxies. The calculations, when displayed as a movie, clearly display how incipient structures unfold and evolve. Within each galaxy-scale clump, gravity enhances the contrasts still further; gas is pulled in, and compressed into stars.

And there is one very important point. The initial fluctuations fed into the computer models are not arbitrary – they're derived from the actually observed fluctuations in the temperature of the microwave background, which have been beautifully and precisely delineated over the whole sky by ESA's Planck Spacecraft. The amplitude of the temperature fluctuations is only one part in 100,000, but computing forward, they're amplified by gravity into the conspicuous structures in the present universe.

What about the far future of our universe? In 1998 cosmologists had a big surprise. It was by then well known that the gravity of dark matter dominated that of ordinary stuff – but also that dark matter plus baryons contributed only about 30% of the critical density. This was thought to imply that we were in a universe whose expansion was slowing down, but not enough to eventually be halted. However, rather than slowly decelerating, the Hubble diagram of Type 1a supernovae famously revealed that the expansion was speeding up. Gravitational attraction was seemingly overwhelmed by a mysterious new force latent in empty space which pushes galaxies away from each other.

Moreover, there was independent evidence supporting this. According to Einstein's theory, a straightforward low-density universe would have negative curvature – the three angles of a big triangle would add up to less than 180 degrees. This can be tested from microwave background measurements. That's because there's a straightforward effect that makes the temperature ripples more conspicuous for a particular wavelength – about 300,000 light years. This so-called 'Doppler peak' was first revealed by a balloon-borne experiment called Boomerang, and has been confirmed by the Planck data. It's on an angular scale that's consistent with a flat universe.

If we'd just had the supernova Hubble diagram, some of us wouldn't have been convinced. But these two interlinked and almost simultaneous discoveries together clinched the case. The issue now is the nature of the dark energy – is it time-independent, like Einstein's cosmological constant, or was it different in the past?

Long-range forecasts are seldom reliable, but the best and most 'conservative' bet is that we have almost an eternity ahead – an ever-colder and ever-emptier cosmos. Galaxies accelerate away and disappear over an 'event horizon' – rather like an inside-out version of what happens when things fall into a black hole. All that's left will be the remnants of our Galaxy, Andromeda, and smaller neighbours. Protons may decay, dark matter particles annihilate, occasional flashes when black holes evaporate – and then silence.

5. The Very Early Universe – More Speculative Thoughts

We can trace back to 1 second after the 'beginning'. Indeed, we can probably be confident back to a nanosecond: that's when each particle had about 50 GeV of energy – as much as can be achieved in the LHC – and the entire visible universe was squeezed to the size of our solar system. But questions such as 'where did the fluctuations come from?' and 'why did the early universe contain the actual mix we observe of protons, photons and dark matter?' take us back to the even briefer instants when our universe was hugely more compressed still – when energies were 10^{16} GeV, where experiments offer no direct guide to the relevant physics.

At this point I should insert a 'health warning', because the discourse hereafter becomes much more speculative. According to a popular theory, the entire volume we can see with our telescopes was, at 10^{16} GeV, a hyper-dense blob no bigger than an apple. And it had inflated from something at least a trillion times smaller than an atomic nucleus.

The so-called 'inflationary universe' model is supported by much evidence already. But it may be useful to summarize the essential requirements for the emergence of our complex and structured cosmos from simple amorphous beginnings.

(i) The first prerequisite is of course the existence of the force of gravity – which (as explained earlier) enhances density contrasts as the universe expands, allowing bound structures to condense out from initially small-amplitude irregularities. It's a very weak force. On the atomic scale, it's about 40 powers of ten weaker than the electric force between electron and proton. But in any large object, positive and negative charges almost exactly cancel. In contrast, everything has the same 'sign' of gravitational charge so when sufficiently many atoms are packed together, gravity wins. But stars and planets are so big because gravity is weak. Were gravity stronger, objects no larger than asteroids (or even sugar lumps) would be crushed by gravity. So, although gravity is crucial, it's also crucial that it should be very weak.

(ii) There must be an excess of matter over antimatter.

(iii) Another requirement for stars, planets and biospheres is that chemistry should be non-trivial. If hydrogen were the only element, chemistry would be dull. A periodic table of stable elements requires a balance between the two most important forces in the microworld: the nuclear binding force (the 'strong interaction') and the electric repulsive force that drives protons apart.

(iv) There must be stars – enough ordinary atoms relative to dark matter. (Indeed, there must be at least two generations of stars: one to generate the chemical elements, and a second able to be surrounded by planets.)

(v) The universe must expand at the 'right' rate – not collapse too soon, nor expand so fast that gravity can't pull together the structures.
(vi) There must be some fluctuations for gravity to feed on – sufficient in amplitude to permit the emergence of structures. Otherwise the universe would now be cold ultra-diffuse hydrogen – no stars, no heavy elements, no planets and no people. In our actual universe, the initial fluctuations in the cosmic curvature have an amplitude of 0.00001. According to inflationary models, this amplitude is determined by quantum fluctuations. Its actual value depends on the details of the model.

And here's another fundamental question: how large is physical reality? We can only see a finite volume – a finite number of galaxies. That's essentially because there's a horizon: a shell around us, delineating the distance light can have travelled since the big bang. But that shell has no more physical significance than the circle that delineates your horizon if you're in the middle of the ocean. We'd expect far more galaxies beyond the horizon.

There's no perceptible gradient in temperature or density across the visible universe. This suggests that, even if it's of finite extent, it stretches thousands of times further. But that's just a minimum. If space stretched far enough, then all combinatorial possibilities would be repeated. Far beyond the horizon, we could all have avatars. Be that as it may, even conservative astronomers are confident that the volume of space-time within range of our telescopes – what astronomers have traditionally called 'the universe' – is only a tiny fraction of the aftermath of our big bang.

And there's something else. Plausible models for the physics at the ultra-high energies where inflation could have occurred lead to so-called 'eternal inflation'. 'Our' big bang could be just one island of space-time in a vast cosmic archipelago – a multiverse.

Key questions then are:

(i) Is there one big bang, or many?
(ii) If there are many, are they all replicas of each other, or do they 'ring the changes' on the laws and constants of physics, so that most are 'stillborn' and we find ourselves in one of the subsets that allow complexity to emerge (so called 'anthropic selection')?

This is speculative physics – but it's physics, not metaphysics. There's hope of firming it up. Further study of the fluctuations in the background radiation will reveal clues. But, more importantly, if physicists developed a unified theory of strong and electromagnetic forces – and that theory is tested or corroborated in our low-energy world – we would then take seriously what it predicts about an inflationary phase and what the answers to the two questions above actually are.

If the answer to (ii) is 'yes', then what we call 'laws of nature' may in the grandest perspective be mere local bylaws governing our cosmic patch. Many patches could be still-born or sterile – the laws prevailing in them might not allow any kind of complexity. We therefore wouldn't expect to find ourselves in a typical universe – rather, we'd be in a typical member of the subset where an observer could evolve.

I started by describing newly discovered planets orbiting other stars. I'd like to give a flashback to planetary science 400 years ago – even before Newton. At that time, Kepler thought that the Solar System was unique, and Earth's orbit was related to the other planets by beautiful mathematical ratios involving Platonic regular solids. We now realise that there are billions of stars, each with planetary systems. Earth's orbit is special only insofar as it's in the range of radii and eccentricities compatible with life (e.g. not too cold and not too hot to allow liquid water to exist).

Maybe we're due for an analogous conceptual shift, on a far grander scale. Our big bang may not be unique, any more than planetary systems are. Its parameters may be 'environmental accidents', like the details of the Earth's orbit. The hope for neat explanations in cosmology may be as vain as Kepler's numerological quest.

If there is a multiverse, it will take our Copernican demotion one stage further – our solar system is one of billions of planetary systems in our Galaxy, which is one of billions of galaxies accessible to our telescopes – but this entire panorama may be a tiny part of the aftermath of 'our' big bang – which itself may be one among billions. It may disappoint some physicists if some of the key numbers they are trying to explain turn out to be mere environmental contingencies – no more 'fundamental' than the parameters of the Earth's orbit round the Sun. But in compensation, we'd realize space and time were richly textured – but on scales so vast that astronomers aren't directly aware of it – any more than a plankton whose 'universe' was a spoonful of water, would be aware of the Earth's topography and biosphere.

(When the multiverse is mentioned, it's sometimes asserted that domains that aren't observable don't count as a part of science. But I think that's the wrong way to look at it. We can't observe the interior of black holes, but we believe what Einstein says about what happens there because his theory has gained credibility by agreeing with data in many contexts that we can observe. Likewise, if we had a theory that described physics at 10^{16} GeV that had been corroborated in other ways, then if it predicts multiple big bangs we should take that prediction seriously.)

We've made astonishing progress. Fifty years ago, cosmologists didn't know if there was a big bang. Now, we can draw quite precise inferences back to a nanosecond. So, in 50 more years, debates that now seem flaky speculation may have been firmed up. But it's important to emphasize that progress will continue to depend, as it has until now, 95% on advancing instruments and technology – less than 5% on armchair theory.

6. A Digression

General relativity and quantum theory are the twin pillars of twentieth-century physics. But they haven't yet been meshed together into a single unified theory. In most contexts, this does not impede us because the domains of relevance do not overlap. Astronomers can ignore quantum fuzziness when calculating the motions of planets and stars. Conversely, chemists can safely ignore gravitational forces between individual atoms in a molecule because they are nearly 40 powers of ten feebler than electrical forces. But at the very beginning, *everything* was squeezed so small that quantum fluctuations could, as it were, 'shake' the entire universe.

We ourselves are midway – on a log scale – between atoms and stars: large enough, compared with atoms, to have layer upon layer of intricate structure; but not so large that we're crushed by our planet's gravity. (The geometric mean of a proton mass and the Sun's mass is 50 kg). To understand ourselves, we must understand the atoms we're made of, and the stars that made those atoms. Even an insect, with its layer upon layer of complexity is harder to understand than a star, where intense heat and compression by gravity precludes complex chemistry.

And that is why 99% of scientists are neither particle physicists nor astronomers: they work neither on the very small nor on the very large, but, instead, on the very complex, which presents the greatest challenges of all.

The sciences are sometimes likened to different levels of a tall building – particle physics on the ground floor, then the rest of physics, then chemistry, and so forth: all the way up to psychology – and the economists in the penthouse. There is a corresponding hierarchy of complexity – atoms, molecules, cells, organisms and so forth.

But the analogy with a building is poor. The 'higher level' sciences dealing with complex systems aren't imperilled by an insecure base, as a building is. Each level has its own autonomous concepts and theories. To understand why flows go turbulent, or why waves break, subatomic details are irrelevant. We treat the fluid as a continuum. An albatross returns predictably to its nest after wandering ten thousand miles in the southern oceans. But this is not the same kind of prediction as astronomers make of celestial orbits and eclipses.

Everything, however complicated – breaking waves, migrating birds and tropical forests – is made of atoms and obeys the equations of quantum physics. But even if Schrodinger's equation could be solved, its solution wouldn't offer the enlightenment that scientists seek. Reductionism is true in a sense. But it's seldom true in a *useful* sense. Each science has its own autonomous concepts and laws.

Phenomena with different levels of complexity are understood in terms of different irreducible concepts – turbulence, survival, alertness and so forth. The brain is an assemblage of cells; a painting is an assemblage of chemical pigment. But in both cases what's important and interesting is the pattern and structure – the emergent complexity.

That was a digression to highlight the unity of science – plus a gesture of deferential modesty towards the 99% of scientists who are neither particle physicists nor cosmologists.

7. Concluding Perspective

Finally, I want to draw back from the cosmos – even from what may be a vast array of cosmoses, governed by quite different laws – and focus closer to the here and now. I'm often asked: is there a special perspective that astronomers can offer to science and philosophy? We view our home planet in a vast cosmic context. And in coming decades we'll know whether there's life out there. But, more significantly, astronomers can offer an awareness of an immense future.

The stupendous timespans of the evolutionary past are now part of common culture (although maybe not in, say, Kentucky or in some parts of the Muslim world). Darwinism tells us how our present biosphere is the outcome of more than four billion years of evolution.

But most people still somehow think we humans are necessarily the culmination of the evolutionary tree. That hardly seems credible to an astronomer – indeed, we are probably still nearer the beginning than the end. Our Sun formed 4.5 billion years ago, but it's got 6 billion more before the fuel runs out. It then flares up, engulfing the inner planets. And the expanding universe will continue – perhaps forever – destined to become ever colder, ever emptier. To quote Woody Allen, eternity is very long, especially towards the end.

Any creatures witnessing the Sun's demise 6 billion years hence won't be human – they'll be as different from us as we are from a bug. Post-human evolution – here on Earth and far beyond – could be as prolonged as the Darwinian evolution that's led to us – and even more wonderful. And of course this evolution is even faster now – it happens on a technological timescale, operating far faster than natural selection and driven by advances in genetics and in artificial intelligence (AI). We don't know whether the long-term future lies with organic or silicon-based life.

But my final thought is this. Even in this 'concertinaed' timeline – extending billions of years into the future, as well as into the past – this century may be a defining moment. Over most of history, threats to humanity have come from nature – disease, earthquakes, floods and so forth. But this century is special. It's the first where one species – ours – has Earth's future in its hands, and could jeopardize life's immense potential. We've entered a geological era called the anthropocene.

Our Earth, this 'pale blue dot' in the cosmos, is a special place. It may be a unique place. And we're its stewards in an especially crucial era. That's an important message for us all, whether we're interested in astronomy or not.

About the Author

Martin Rees is a cosmologist and space scientist. He is based in Cambridge, UK, where he has been Director of the Institute of Astronomy and Master of Trinity College. He was President of the Royal Society from 2005–2010. In 2005 he was appointed to the UK's House of Lords. He belongs to numerous foreign academies, including the US National Academy of Sciences, the Russian Academy and the Pontifical Academy. Among his many awards are the Balzan Prize, the Gruber Prize, the Bower Award of the Franklin Institute, the Crafoord Prize and the Templeton Prize. He has served on the Boards of the British Museum, the Science Museum, NESTA, the Princeton Institute for Advanced Study and on many other bodies connected with education, space research, technological risks and international collaboration in science. He is a Member of the Academia Europaea. The latter awarded Martin Rees its Erasmus Medal in 2016.