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How Special is our Universe? Fine-Tuning and Cosmological Natural Selection

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Fine-tuning in Nature

If the fundamental constants of nature differed from their measured values, life as we know it would not have emerged. Imagine a universe in which the fine structure constant was slightly larger or smaller than the actual value that we measure. Stars like the sun are witness to a titanic battle between the forces of electromagnetism and gravity. The solar system formed from the ashes of burnt-out stars. Displace this equilibrium slightly and the very existence of nuclear-burning stars is at risk. In such a universe, stars would never have formed, or might have collapsed to black holes. Perhaps there are many other universes, most of which are uncongenial to life. Theories of the multiverse are designed to accommodate the possibility that there are only incredibly rare examples of life-containing universes. We live in one of these, whether by cosmological natural selection or by the consequences of an ultimate theory that has yet to be formulated.

Simple physical arguments can account for the fundamental scaling relations of stars and galaxies. To be fair to simulators, the dispersion in these relations contains most of the relevant physics, and can only be adequately explored via state-of-the-art numerical simulations over a vast and currently inadequate dynamical range. Here however I focus here not on the scaling laws but on the actual scales: characteristic, minimum and maximum, from protostars to stars, galaxies and supermassive black holes. Unlike the scientists of antiquity, astronomers today have two significant advantages. One consists of the huge telescopes that peer back in time to the edge of the observable universe. A second is the mastery of modern physics and mathematics, that has discouraged most of the philosopher cosmologists, and their theologian counterparts, from entering the fray. I do not mean to be completely discouraging: there are fundamental limits to the questions that cosmology can answer.

Carbon

> *Things are the way they are because they were the way they were.*
>
> --Fred Hoyle 1915-2001

Hoyle helped to invent the Steady State Universe, which for two decades provided an alternative to the Big Bang theory. His theory was eventually falsified, following the discovery of the cosmic microwave blackbody fossil radiation, proof of a hot beginning, and as more and more observations demonstrated that the universe had evolved.

However, Hoyle did get something right. His anti-Big Bang views led him to an equally important cosmogonic truth. He pioneered the idea that in the fiery cores of stars, all of the heavier chemical elements are synthesized by thermonuclear reactions. The logic behind this argument immediately ran into an obstacle. It seemed to be impossible to synthesize carbon in stars, or indeed anywhere else. This led Hoyle to make an amazing prediction.

Carbon is very abundant in the universe. It is formed by thermonuclear reactions in the cores of stars. First hydrogen fuses into helium, supplying the energy that powers stars like the sun. As the star exhausts its hydrogen supply, the core contracts and heats up, and three helium nuclei fuse into a carbon nucleus. However, fusing the necessary three helium nuclei together was found to occur far too slowly. When thermonuclear powering of stars was first understood in the 1950s by hydrogen fusing into helium, and the consequent release of thermonuclear energy that powers our sun, there was found to be a serious problem in extending these ideas to the synthesis of the heavier elements. The hope was that dying stars, as they explode if massive enough, would release their enriched contents into the surrounding interstellar medium.

But there was a cosmic log jam. The intermediate nucleus, beryllium of atomic mass 8, formed from two helium nuclei each of mass 4. However the ladder stopped here. The combination of newly minted beryllium with a third helium nucleus has too much energy to form more than a trace amount of carbon, of mass 12. Yet carbon is a very abundant element.

To provide a much larger fusion probability for beryllium to combine with helium, Hoyle predicted in 1954 a resonance at 7.68 MeV in the carbon nucleus. It is as though the carbon nucleus oscillates in size and briefly becomes large enough to contain the beryllium and helium nuclei, giving them time to fuse together before they escaped. This was the only solution to an otherwise impossible situation. It was just a hypothesis, born out of desperation. Three years later, the resonance was measured. This prediction allowed carbon to form in abundance, as observed, and provided the key ingredient to later set the scene for life as we know it, where carbon is a key ingredient. Hoyle made the first anthropic prediction: the existence of life sets strong constraints on physics and indeed leads to specific predictions of fundamental quantities.

Stars

Eddington once famously said that a physicist on a cloud-bound planet could predict that there are stars. What is a star? A galaxy is an agglomeration of many billions of stars. All devolves around knowing the masses of the stars. Why should a star like the sun weigh in at two billion trillion trillion tons? No more, no less. And all other stars, countless in number, are between a tenth of and a hundred times the mass of the sun.

Eddington reasoned this way. A star is a giant ball of gas supported by gravity. Here is what he wrote in 1926 (with very slight amendment):

> We can imagine a physicist on a cloud-bound planet who has never heard tell of the stars calculating the ratio of radiation to gas pressure for a series of globes of gas of various sizes, stating say, with a globe of mass 10gm, then 100 gm, 1000 gm and so on, so that her nth globe contains 10n gm. Regarded as a tussle between gas pressure and radiation pressure, the contest is overwhelmingly one-sided except between Nos. 33-35, where we may expect something interesting to happen. What happens is the stars. We draw aside the veil of cloud beneath which our physicist has been working and have her look up at the sky. There she will find a thousand million globes of gas nearly all of mass between her 33rd and 35th globes, that is to say, between 1/2 and 50 times the suns mass.

Eddington realized that the pressure of radiation is highly destabilizing. He had studied giant globes of gas supported by the balance between their own gravity and the interior pressure of the gas. But as one turned up the mass, and consequently the gravity, the centre became so hot that the pressure of radiation exceeded that of the gas. This was enough to blow the globe of gas apart. And if the mass was too small, the centre of the globe was so cold that it could not resist gravity, so he reasoned. That is how he deduced, from pure thought, the mass range of the stars. In the century that followed, astronomers measured the masses of many stars, typically by using the orbits in binary star systems, and confirmed Eddington's reasoning. Most stars are similar in mass to the sun, more typically half or a third the mass of the sun.

Formation of the Stars

Once we converge on the notion of a star, we wonder where they came from. This inevitably leads us into a description of the first stars in the universe. Although they disappeared long ago, they left traces and fossils that we try to decipher.

But let us begin with the nearest star, our Sun. Firstly, how did it form? A cloud of interstellar gas cooled down. It collapsed under its own gravity. The cloud fragmented into dense clumps of cold gas. The gas is so dense that it is predominantly molecular, and cools much more efficiently than atomic hydrogen. Each of these clumps of dense gas gave birth to a star.

The forming star is surrounded by a nebula of cold gas and dust that has too much rotation to collapse. Instead, the nebula cools and forms a dusty gaseous disk that spins around the central object. We refer to this as a protostar, destined, as it shrinks further, to be a star. The protostellar disk has its own destiny: it will fragment into planets. Most of the stars were a tenth of the mass of the sun. Relatively few were ten solar masses or more. Most stellar mass is in stars of around half the mass of the sun. And then there were the sun-like stars, around which earth-like planets are found. Fewer stars are very massive, but they are luminous and stand out from crowded stellar fields.

Stellar Aging

The more massive a star, the more rapidly it ages. Stars radiate by thermonuclear burning of hydrogen in their cores. A helium nucleus has atomic mass 4. It consists of two protons and two neutrons. It forms by combining four protons along with two electrons. The helium nucleus weighs seven percent less than four protons. The missing mass is released as energy via Einstein's famous equation $E = mc^2$. That is how the sun battles gravity. Thermonuclear energy supplies the thermal pressure that supports the sun. The fuel supply is good for billions of years in the case of sun-like stars, although only millions of years for stars that are twenty solar masses.

When the hydrogen fuel supply in the core of the sun, where it is hot enough to burn, is exhausted, the sun contracts, and the core heats up. Helium is ignited, and it burns by thermonuclear reactions into carbon. This reaction releases so much luminosity that the outer part of the sun swells up into a red giant. Our sun is fated to become a red giant in about 4 billion years. At this time, the sun's atmosphere would encompass the orbit of the earth, burning any surface organic material into ashes. Once the helium energy supply is exhausted, the core contracts into a white-hot star about the size of the earth, but a million times denser. We call this a white dwarf. It is mostly oxygen and carbon. The atmosphere of the red giant precursor is ejected in the beautiful phenomenon that we see as a planetary nebula. The white dwarf gradually cools down.

Our galaxy is teeming with old white dwarfs, descendants of sun-like stars. A star that is ten or thirty times the mass of the sun has a greatly accelerated evolution. It burns up its nuclear fuel at a rate that goes as the cube of its mass. This means that its lifetime as a hydrogen-burning star may be only a hundred million years or even a few million years. These are tiny time-scales in the grand cosmic scheme; many such events occur over the ten billion year time-span of our galaxy. So we can use our galaxy as an astronomical zoo: it contains stars at all stages of their evolution, from birth to death. We can visualize the birth, adolescence, maturity and old age of stars.

Planets

What is special about a planet? Planets are neither too big nor too small. If too massive, they become stars, and if too small, we recognise them as asteroids, or in the case of Pluto, a dwarf planet. What is special about the Earth? For one thing, it is in the right place, relative to the sun, in the habitable zone. We believe this is purely by chance, by a roll of the gravitational dice when the solar system formed. The discovery of thousands of exoplanets, a few of which are earth twins, confirms this idea. These are prime targets for future space telescope observations that will search for biosignatures, the presence of, for example, oxygen in exoplanet atmospheres that might indicate the presence of an oxygen-rich atmosphere that is necessary for life.

Here is another application of earth-like planets to a fine-tuning issue. The tallest known human, an American called Robert Wadlow, had a vertical span of 8ft 11 inches. The Nepali Chandra Bahadur Dangi was the shortest adult ever recorded, at 21.5 inches. The average human height is levelling off to about 5ft 5 inches, a respectable height for much of the world's population. Of the mean height is more in the US or UK, about 5ft

10 inches. . But the observed distribution of human heights fills only a small part of this possible range. Why is this? And where are the giants, as in the mythological world of Jack and the Beanstalk? And where are the Lilliputians?

We know the answers. Gravity makes life most unhealthy above a certain height. Our bodies could not be supported, and we would topple over. Survival of the fittest makes life difficult for the dwarfs and for the giants among us. Genetic evolution with an assist from gravity eventually narrows the height range to the observed distribution. Biology and physics provide the answers.

Galaxies

What is special about a galaxy? For one thing, there is its mass in stars. To form stars, the baryons must be able to cool within a collapse time-scale. Cooling is a necessary condition for star formation. From this requirement, theory is able to account for the minimum and maximum masses of the luminous stellar components of the observed galaxies. For the smallest, those that form first in the early universe, trace amounts of hydrogen molecules providing the cooling catalyst. Dissipation of energy is essential in order to form stars. For massive galaxies, that form later, the cooling is too slow if the interstellar gas density is too low. In this case, star formation becomes inefficient. More massive galaxies do indeed form by gas accretion on longer time scales, but the process is relatively rare, occurring mostly at the centres of galaxy clusters.

Such remarkably simple arguments yield a minimum baryonic mass of a million solar masses and a characteristic mass of a hundred million solar masses for galaxies. These masses accord well with observations. There are problems however with the predicted number densities, both of small and of massive baryonic objects. Feedback is the usual explanation. This is the idea, based on observations, that when massive stars die via explosions as supernovae, the hot debris of the star is ejected at high velocity, up to a tenth of the speed of light, into the surrounding cold interstellar medium. The sudden injection of energy expels the cool gas, especially in the less massive galaxies, and curtails any further star formation. This process effectively diminishes the numbers of small galaxies by making them almost invisible because the reduced gas supply removes the raw material for forming stars.

For massive galaxies, the relatively diminished frequency is explained not by supernovae but from energy released by gas accreting onto central supermassive black holes. These galaxies undergo a quasar-like phase, in their gas-rich formation phase. The gas supply is mostly ejected and star formation is quenched.

Multiverse

The greatest mystery in the universe is the dark energy that dominates its energy density today. But our best theories of particle physics predict a value that is too large by 120 powers of 10. One solution is to bring in the anthropic principle, the argument that only in the infinitesimal subset of universes with little dark energy could life have emerged. And here we are.

There are many possible universes inhospitable to our existence. In particular, theories of quantum gravity count some 10^{500} realizations of the universe, in which the various fundamental constants of nature differ. In this so-called multiverse, all universes are equally real, though we can only hope to explore one of them, our universe. Given the staggering array of alternatives, it becomes exceedingly improbable that our observed universe should even exist. Except that we don't know how to compute probabilities in the multiverse.

How do we estimate the odds of an infinite multiverse? We have absolutely no idea! For example, in our universe, leprechauns are rarer than people. In a multiverse, there are infinite numbers of both. So what's the ratio? Let us take the parsimonious view, if only to avoid unresolvable philosophical dilemmas, then there is only one universe. We follow Einstein's dictum:

Everything should be kept as simple as possible, but no simpler.

How special was the beginning of the universe? Were we in some very special state? And can we understand why the universe is so close to being Euclidean, not only now, but especially when it began? Flatness is relative to the epoch that we examine, but only if the universe began in some arbitrarily curved space. Once perfectly flat, always perfectly flat. Topology, in this case of an infinite Euclidean space, does not change. If the best scientific theories are the simplest, then this provides a decent guess about how it began.

And inflation is still our best bet, with only six numbers needed to characterize the cosmic microwave background map of our cosmic beginnings, the tiny fluctuations that seeded all structure in the universe on large-scales. Perhaps the rest was all downhill. More and more complexity developed as non-linear structures developed, and when chemistry and then biology emerged.

Such reasoning might suggest that the complexity of the universe emerged in a top-down process, as galaxies, stars and planets formed. This is a contrarian view. Physics is usually considered bottom-up, as atomic physics emerges from nuclear physics, which itself emerges from particle physics. Biological complexity, likewise, is usually considered to be bottom-up, going from green algae up to homo sapiens. But there are counter-examples, ranging from computing and sociology to neurology and brain science. And quantum uncertainty ultimately bedevils bottom-up approaches on the smallest micro-scales.

Design: intelligent or natural?

The parsimony of the scientific approach leads us into the muddy waters of theology, where science sometimes challenges belief. This was never the case for the founder of Big Bang cosmology, the Belgian priest Georges Lemaitre, who reasoned that in 1931:

> Everyone who believes in a supreme being believes also that God is essentially hidden and may be glad to see how present physics provides a veil hiding the creation.

But the pathway was less clear in the eighteenth century. William Paley was astounded at the complexity of nature:

> If a pocket watch is found on a heath, it is most reasonable to assume that someone dropped it and that it was made by a watchmaker, not by natural forces.
>
> — *William Paley 1743-1805*

His argument was persuasive, and implied that one could deduce the hand of God, presumably responsible for the watchmaker, by observing nature. It captured the attention of great scientists of his time. In fact, one notable scientist Isaac Newton, discoverer of mechanics and of gravity, had reached much the same conclusion a century before Paley:

> This most beautiful system of the sun, planets and Comets, could only proceed from the counsel and dominion of an intelligent and powerful Being.
>
> — *Isaac Newton 1643-1727*

The situation changed dramatically once ideas about evolution by natural selection were developed. Charles Darwin forcefully led the charge against intelligent design, writing

> Now that the law of natural selection has been discovered, we can no longer argue that, for instance, the beautiful hinge of a bivalve shell must have been made by an intelligent being, like the hinge of a door by man. There seems to be no more design in the variability of organic beings and in the action of natural selection, than in the course which the wind blows.
>
> — *Charles Darwin 1809-1882*

Fine-tuning occurs in forming carbon, stars, galaxies, massive black holes, the beginning of the universe, and even theology perhaps…it's all a matter of local complexity, self-regulation, and physical laws, as Darwin concluded:

Everything in nature is the result of fixed laws.

Back to Fine-tuning

The universe we observe around us, that's astronomy, and the universe of our origins, that's cosmology, are continually giving us surprises. Each new discovery yields as many questions as answers. It is clear that the fundamental constants of nature must have very specific ratios in order to account for the observed universe, and the observers of the universe, namely us. Do these dimensionless numbers emerge from a mathematical construct, so we would be elements in a sort of cosmic computer? Probably not, as we know, thanks to Kurt Godel, that mathematics is incomplete.

That takes us to physics: do we need a multiverse to provide the choice of constants of nature from which only an infinitesimal subset led to our emergence? This is pure metaphysics, since the multiverse hypothesis is untestable. Some of my colleagues argue, so what: if it is a sufficiently elegant and explanatory theory, that's all we need. We may as well give it our trust to take us forward.

Or do we advocate the parsimonious approach, whereby we consider that 10^{500} or more constants of nature are simply too many? Indeed the latest calculations from string theory tell us that there are some 10^{172000} different manifolds to be considered in the multiverse, each no doubt with its own set of fundamental constants. There is no prospect of cosmic boredom with this many choices. But whether a multiverse constructed on such a basis provides a scientific explanation of nature is another matter. With enough other free parameters added to the science of aeronautics, one would infer that pigs can fly. And indeed, maybe they do, in a distant galaxy in a multiverse far away, somewhere conveniently beyond our horizon.