OUT OF THIS WORLD AND INTO THE NEXT

OUT OF THIS WORLD AND INTO THE NEXT

Notes from a Physicist on Space Exploration

ADRIANA MARAIS

Profile Books

First published in Great Britain in 2025 by
Profile Books Ltd
29 Cloth Fair
London
EC1A 7JQ
www.profilebooks.com

1 3 5 7 9 10 8 6 4 2

Typeset in Sabon by MacGuru Ltd
Printed and bound in Great Britain by
CPI Group (UK) Ltd, Croydon CR0 4YY

A CIP catalogue record for this book is available from the British Library.

ISBN 978 1 80081 980 1
eISBN 978 1 80081 983 2

MIX
Paper | Supporting responsible forestry
FSC® C171272

ACKNOWLEDGEMENTS

I feel like this book has written itself, so my heartfelt thanks and appreciation go out to all people who have dedicated their lives to contributing to human knowledge, and to everyone I've known for our cherished interactions that have shaped the thoughts compiled here. Especially my parents, siblings, friends, partners and mentors, who have deeply influenced the way I see the world. I am grateful for having had the opportunity to share my ideas with hundreds of audiences on all continents of our planet and I thank those of you who have challenged and broadened my thinking. We can live in harmony with each other and the environment, wherever in the Universe we may be. Thank you to our Earth for having put up with us for so long while we learn how.

CONTENTS

Part II: Who are we?

Part III: Where are we going?

PREFACE

'A species far-wandering and equipped for distant migrations, through inborn wanderlust or otherwise, would always have a better chance than one confined.'
Eugène Marais (1871–1936)

When I first read about the call for volunteers for a one-way mission to Mars in 2012, I felt suddenly nauseous, struck by a childhood memory that rushed back to me with perfect clarity: as my black plastic scooter rattled down the brick driveway at playgroup one day, out of the blue I had a series of imaginings. There was a global radio broadcast (this was the pre-Internet 1980s): a call for a volunteer to go on an urgent journey to find a new home for humanity. The volunteer would travel through space far away from Earth, and send back a message if a suitable planet was discovered. I vividly pictured myself looking out of a small round window with a notebook in hand. The distant stars were stationary although I was travelling fast. It was dark and I was alone. I hoped for the sight of land, the welcome arc of a planetary horizon, but knew that I may not live long enough to get there. While this time I turned round to kick back up the hill on my scooter, I silently vowed that I would volunteer for such a critical mission for humanity, even if I may not come back. I must have been four or five. It would be more than twenty years until I and people all around the planet would be confronted by this same scenario: would you volunteer to leave Earth to establish the first off-world society?

When most people think about 'home', an area much smaller than the surface of Earth comes to mind. For many, Earth is their favourite planet. But for those who feel a curiosity, an affinity and indeed a sense of belonging with that overwhelming majority of what is beyond, Earth is but a pale blue dot in a Universe of star stuff waiting to be known. Here, I'd like to share my wonder at being alive at this extraordinary time on Earth. Four billion years of evolution on this planet have brought us to the brink of a new era: just decades since we first went to space, it won't be much longer before we're building new worlds beyond home.

PART I

WHERE DO WE COME FROM?

One night, at a big space conference, a friend and I decided to sneak into a prestigious invite-only dinner (to which we were not invited). It was 2016 and we knew that the founder of SpaceX, Elon Musk, would be presenting his plans to make humanity multiplanetary on the main stage the following day. Who knew whom we might meet there. From the door we identified two empty seats, strode briskly past security and sat down as casually as possible. I nonchalantly took a large gulp of what I thought might be juice in front of me. It turned out to be tequila – we were after all in Mexico. The man next to me looked impressed that I had swallowed the whole lot, and, skipping the small talk, asked what I felt when I look out into the stars.

'A sense of belonging,' I replied without hesitation. The man was a cosmonaut, and a discussion about our place in the Universe ensued which has remained deeply etched into my memory to this day.

As children, our homes are the houses we grow up in, surrounded by the people and places that become familiar to us. As we grow up, our perception of home grows with us, and as we learn about space and time and causality – we may not frame it in those words – a question every child asks is: where do we come from? While we have all wondered about this at some point, a few of us spend lifetimes searching for answers. The quest to understand where we come from, to understand our place, our home, in the Universe is driven by an innate curiosity about the reality beyond our world, by our imagination of what lies beyond our current experience.

Did you know that 10 percent of our bodies is as old as the Universe itself? According to our best theory of how it started, anyway – the Big Bang Theory – and the rest of us is made up of the dust of exploded stars. To understand our origins, our place in the Cosmos in which we find ourselves, we must follow the allure of the unknown beyond Earth, back in time to where it all, and we all, began, on a timeline beginning billions of years ago.

1

THE UNIVERSE

In the beginning: the Big Bang

In the broadest sense, the place that we are from is the Universe. And, according to current scientific theory anyway, that is where we will remain, since while space is vast from our human perspective, there is in fact a boundary to reality: the edge of the Universe, beyond which no travel, communication or any kind of interaction is possible.

As the story goes, in the beginning, around 14 billion years ago, the entire Universe burst out from an infinitesimally small point, in an event first jokingly referred to as the 'Big Bang'; the name, however, has stuck. Over the next few millionths of a second, the Universe rapidly expanded and was filled with an incredibly hot and dense plasma – a fourth state of matter not solid, liquid or gas – made up of the fundamental building blocks of matter called quarks as well as negatively charged particles called electrons. Within the first second, the quark soup cooled enough to form matter as we know it, including protons and neutrons – the particles that together make up the nuclei of atoms.

A full-scale simulation to test our theory of the Big Bang requires more energy than we can conceive of controlling. However, the world's largest particle accelerator, the Large Hadron Collider at CERN, smashes things like the nuclei of atoms together at extremely high energies, forming something akin to the quark soup thought to have existed shortly after the Big Bang. Observing these mini big bangs gives us some clues about what was happening in the early Universe.

We've learned that as the Universe continued to expand and the temperature and the density decreased, some 380,000 years after the Big Bang, protons and neutrons combined into positively charged nuclei and attracted the free negatively charged electrons roaming around to form the simplest atoms, hydrogen and helium. As these atoms formed, excess energy was released in the form of photons – the particles that make up light – and with the free electrons out of the way, these photons of light could travel uninterrupted. Before this, the Universe was opaque. And then it became transparent as the oldest light in the Universe streamed out. Awe-inspiringly, the now-cooled remnants of this light are still observable today in the form of the Cosmic Microwave Background.

This is as far back as we can see, as these primordial photons arrive at our planet after travelling through the expanding Universe for billions of years. We only noticed this backdrop to our Universe around fifty years ago. At first mistaken for interference from pigeon droppings on the equipment, the Cosmic Microwave Background was accidently detected by astronomers Robert Wilson and Arno Penzias. After the pigeons were removed and the new supersensitive antenna cleaned, they realised that the noise they were picking up was actually a signal, and that the space in between stars and galaxies was not completely dark, as was previously believed. In the background, coming from all directions at all times, is a faint signal: an ancient bath of light cooled to just slightly above absolute zero, left over from the formation of matter in the Universe billions of years ago.

Coupled with our observations that everything is moving away from us and that most galaxies are moving away from each other, faster and faster, implying that the Universe is expanding at an accelerated rate, analysis of the Cosmic Microwave Background lets us wind back the clock. By doing this, we can estimate the age of the Universe: somewhere in the region of 13.8 billion years.

Looking at the oldest light tells us not just about when the Universe came into existence, but also about the earliest matter: after 380,000 years the Universe consisted of mostly hydrogen and some helium atoms. In fact, the Big Bang is the only process we know of that produces hydrogen in significant amounts in space. Therefore, the water molecules making up more than half of your body contain hydrogen atoms (constituting around a tenth of your mass) that are almost 14 billion years old!

Though the beginning of the Universe may feel so very far away, there is something magical in the knowledge that we are all bathed in faint, ancient light from the beginning of time. That within each of us lives the entire history of our Universe.

After the formation of the first hydrogen and helium atoms, clumps of this early matter began to gather under the force of gravity into hot, bright, dense objects: the earliest stars were born. Within the nuclei of the atoms that make up matter, vast amounts of energy are stored; under the extreme temperatures and pressures in their cores caused by the immense gravity there, stars release this nuclear energy in a process called fusion, which results in hydrogen nuclei being fused into helium nuclei. The mass of the helium produced is less than the two input hydrogens, and according to the revelation that energy and matter are interchangeable, as first described by physicist Albert Einstein's famous equation more than a century ago, the difference comes streaming out in the form of light as well as particles.

Gradually, structures of matter of increasing size began to emerge, and after just a few hundred million years collections of early stars formed galaxies. Once a star has burned all of its hydrogen it begins to die. While most stars eventually fade away, some meet their ends in spectacular explosions called supernovae. The energy released during the lifetime of stars and during such supernovae events results in the formation of the rest of the elements comprising the periodic table: the oxygen, carbon, nitrogen and so on, which make up all matter, including our bodies. As astronomer Carl Sagan said, we are made of star stuff.

The Big Bang is our best-supported theory of how the Universe began: with an ancient explosive force forming a reality expanding at increasing speeds in all directions. Tempering any hubris, however, I think we can agree that some significant unresolved issues in our understanding of the Cosmos remain.

Looking back at the history of the Universe in this way has led us to the somewhat awkward conclusion that the majority of what is out there – a whopping 95 percent – remains hidden from sight. If our current theories are accurate and the rate of expansion of our Universe is continuing to accelerate over time, then there must be a mysterious, so far unseen force causing this acceleration. We call this dark energy. Furthermore, observations of objects in the Universe, for example galaxies rotating at such high speeds that their gravity shouldn't be able to hold them together, don't make sense unless a large amount of unseen stuff – dark matter – is also playing a role. We have not yet observed dark matter directly, precisely because it is 'dark'; it doesn't interact with light or matter as we know it, making it impossible to detect with existing instruments. Its existence is therefore inferred from such observed anomalies. More recent results may indicate that dark energy itself is evolving with time, once again flummoxing our understanding of cosmology.

Another challenge in understanding the Universe is that we have not yet managed to unify our theory of reality on the very small scales where particles like quarks, electrons and photons exist – quantum mechanics – with our theory of space and time in a Universe containing large quantities of the very small – general relativity.

Quantum theory tells us some strange things, some of which we'll get to later, but basically that what we observe in the Universe consists of quanta, or units that can't be broken up further: light is made up of indivisible particles called photons; electric current, of electrons; and protons and neutrons are made up of quarks (all of which do indeed so far seem to be indivisible). And these particles don't behave like things we are used to: they can manifest as particles or as waves with frequencies and wavelengths. Furthermore, fundamental particles with a shared history – like the Big Bang – can retain special quantum correlations appearing to transcend our understanding of space and time: in what Einstein called 'spooky action at a distance', also termed entanglement, what happens to one impacts the other seemingly instantly no matter how far apart they are. While we don't yet know if the space and time in which these quantum objects exist are also quantised, these quanta certainly don't age like we do, moving equally forwards or backwards in time according to the quantum mechanical equations that describe them.

In the theory of general relativity, space and time are continuous, combined into a single concept called spacetime; and things with mass bend spacetime. In a memorable physics demonstration, Tony Fairall, one of my astronomy lecturers, wrapped a wooden frame in cling film, this surface being a two-dimensional analogy to four-dimensional spacetime. He placed a large marble in the centre of the surface, which caused the cling film to sag in the middle. He then placed a smaller marble at the edge of the surface, gave it a push, and we watched as it circled inwards towards the big marble. Similarly, a star (the big marble) curves the spacetime round it, such that a planet (the small marble) in the vicinity, given some initial velocity, begins to orbit the star; without the friction of the cling film, this orbiting continues for a long time.

The idea that mass bends spacetime to produce gravity, with the result that things in the neighbourhood travel in curves, was rather spectacularly demonstrated just a few years after Einstein proposed the theory in 1915. If Einstein's theory were accurate, the light from stars positioned behind the Sun as seen from Earth should be bent by its gravity and they should therefore appear to be in different positions from where they actually are. An eclipse, where the Moon blocks enough sunlight for stars near the Sun to be seen from the surface of Earth, was an ideal opportunity to test this. And indeed, during the total solar eclipse of 1919, measurements showed that Einstein's predictions were correct: the locations of the stars now visible appeared displaced compared with their actual positions because the Sun was in between and bending the spacetime, and thus the light travelling between the stars and Earth.

Without going into too much of the detail developed by thousands of physicists over the past few hundred years, as a result of the inconsistencies between these theories, in particular in our understanding of time, some conundrums remain. For example, it's difficult to say whether there are in fact 10 to the power of 80 electrons (1 followed by 80 zeros) or just one electron in the Universe. Physicist Richard Feynman said he received a telephone call one day from fellow physicist John Wheeler:

'Feynman, I know why all electrons have the same charge and the same mass.'

'Why?' asked Feynman.

'Because, they are all the same electron moving backwards and forwards in time!'

It is worth mentioning at this point that while we have casually given times in units like years here, our understanding of time is limited by our inability to reconcile quantum theory with general relativity: time in quantum theory is absolute, steadily ticking away at all places in the Universe, whereas in general relativity it is dynamical, since gravity can bend spacetime and therefore time itself. We can, however, define cosmic time as a time that all observers co-moving with the expansion of the Universe agree upon. Then we can say that the Universe is 13.8 billion years old. Neither theory, unfortunately, has much to say about what happened before the Universe burst out, as spacetime, and therefore the physics to describe it, did not yet exist. As physicist Stephen Hawking put it: 'Asking what came before the Big Bang is meaningless, because there is no notion of time available to refer to. It would be like asking what lies south of the South Pole.'

While we are yet to understand why the Big Bang happened, how space and time emerged from this event, and why, of all the physical possibilities, our Universe is one in which stable forms of matter and therefore life can evolve, the stage that we call reality was set. Leaving these mysteries aside for now, let's return to the things we can see: the estimated 5 percent of the Universe that is made of light and matter as we know it, and the spectacular structures that have emerged in the past 14 billion years – the things that have made life on Earth possible.

What we can see: galaxies, stars and exoplanets

So, what has happened in the 14 billion years since the Universe was born? What does it look like now? And where do we fit into all of this?

A galaxy is an immense collection of gas, dust and billions of stars as well as their planetary systems. Galaxies contrast massively with intergalactic space, which is comparatively empty. The stars that make up a galaxy evolve over time, and when they eventually die black holes sometimes form. The explosive supernova that occurs when a large star collapses under the force of its own gravity – typically releasing in just a few seconds as much energy as our Sun does over its entire lifetime – can leave behind a black hole with a mass that can range from a few to hundreds of times the Sun's mass. A black hole is a region where gravity is so strong that nothing, including light, has enough energy to escape. Large galaxies tend to have supermassive black holes at their centres, which can range from 100,000 to even billions of Solar masses. While there's a lot we don't know about supermassive black holes, images of our galactic centre and the supermassive black hole there produced by the Event Horizon telescope and the MeerKAT precursor to the Square Kilometre Array radio telescope continue to shed light on the issue.

Of the trillions of galaxies that have formed in the Universe, all the stars that we can see with our naked eyes in the night sky are in fact in our Galaxy, the Milky Way. The Milky Way is a rather old neighbourhood, relatively speaking, containing at least 100 billion stars, some of which are also the oldest known stars in the Universe. Astronomers determine the age of stars by examining groups assumed to have been formed at similar times. By observing their brightness and temperature and comparing this to models of what stars look like at various points in their evolution, we can estimate the ages of stars. The so-called 'Methuselah Star', named after the longest-lived character in the Bible, is located around 200 light years away from Earth in the constellation of Libra. Methuselah is estimated to have formed soon after the

Big Bang and is one of the oldest stars we know of. Our star, the Sun, is a newcomer by comparison at around 4.6 billion years old.

From our vantage point near the middle of the Galaxy, some 25,000 light years away from both the edge and from the supermassive black hole at the centre, we have very little direct experience of what is out there. Gazing up at the starry night sky, more recently with increasingly sophisticated telescopes to analyse the incoming light signals, we get a sense of infinite possibilities. Are there stars like our Sun out there? Do they also have planets? Could life have emerged there?

Stars shine, making the first question easier to answer: around 20 percent of stars in the Milky Way are Sun-like, meaning that they have near-solar surface temperature, size, chemical composition and age. Planets are much more difficult to detect; and only recently (in 1995) was the existence confirmed of the first planet around a solar-type star beyond our Sun, a so-called exoplanet – by physicist Didier Queloz, a PhD student at the time, and his supervisor Michel Mayor, both of whom won the Nobel Prize in Physics in 2019 for the discovery. Exoplanets don't reflect enough light to be seen directly from Earth. They are instead detected indirectly, for example by observing the wobbling of the star's centre of mass due to a planet's presence, observable in the form of minute changes in the frequency of the star's light. Since that first discovery, thousands of exoplanets have been identified. The oldest known exoplanet, named the Genesis

Planet, is located around 12,400 light years from Earth in the constellation of Scorpius. Genesis is believed to be about 12.7 billion years old; almost three times as old as Earth. Even our nearest exoplanets orbit a star more than four light years away. In sum, our understanding of the ground conditions on planets beyond our Solar System is indeed limited.

While the nearest exoplanets remain beyond our reach, we have sent technology out of the Solar System: in the 1970s the Voyager missions were launched, carrying gold phonograph records engraved with messages from 'a small, distant world, a token of our sounds, our science, our images, our music, our thoughts and our feelings', as described by US president Jimmy Carter at the time. After visiting multiple planets in our own Solar System, these craft became our first technology to venture out of the Solar System into the vast darkness of interstellar space, the space between star systems within a galaxy. Of the three stars in the nearest system called Proxima, Proxima Centauri – first observed from Johannesburg – is the closest. However, at Voyager 1's current speed of over 60,000 kilometres per hour, it is more than 70,000 years away. Even at 300,000 kilometres per second, light takes more than four years to travel there.

This has not stopped big ideas of getting lightweight, fast-moving technology over there in our lifetime to have a look. The Breakthrough Starshot project aims to use the most powerful laser array ever built on a light sail that would accelerate a tiny craft with a mass of around a gram to 20 percent the speed of light. A journey to Proxima Centauri at that speed would take about twenty years. Add another four years for a light signal to return to Earth, and that means we could still be alive to receive the first data from another star system. What we will find there is anyone's guess.

Proxima Centauri b is the closest exoplanet, discovered in 2016 orbiting in the habitable zone of Proxima Centauri. Since all known living organisms require water, for a planet to be in the habitable zone means it orbits a star at a distance where liquid water could exist on its surface, given a dense enough atmosphere. Proxima Centauri b has a mass slightly greater than Earth's, and orbits its star at a distance around twenty times closer to the Sun than Earth, with a year of approximately eleven Earth days. So close to Proxima Centauri, fast-moving flows of charged particles ejected from the star, called solar winds, could be thousands of times more intense than on the surface of Earth; and although the planet may host liquid water, under these conditions its ability to support life is unknown, and will likely remain so until a mission like Starshot can provide us with new information.

Can we take Starshot thinking even further, though? If we can envisage sending our technology to a planet in the habitable zone, what else could we also send there? At a space congress I attended, one memorable speaker proposed that a tiny cargo be added to a Starshot-like craft.

The cargo, terrestrial bacteria, could then be delivered to a suitable planet in the Proxima System to seed life there for study. At the time, from the back of the small lecture room, I found the thought of this hilarious. If we were being featured in an intergalactic reality entertainment channel, the commentary might have gone along these lines: 'In this, the 4 billionth year of the Milky Way's *How to Grow Intelligence from Scratch* saga, the subjects of the experiment on planet Earth propose to run a similar experiment of their own. A pivotal moment for the beings hailing from the ancient Methuselah System in the Libra Constellation who have been running such experiments, so far without success, for most of the age of the Universe. For the first time, the life they seeded on Earth is planning interstellar travel. But will the human society prevail for long enough to get there before the statistically likely self-annihilation we have seen in countless previous episodes? Stay tuned for the season of the Eon!'

But seriously, we estimate that there are more than 40 billion Sun-like stars in our Galaxy, each with, on average, at least one planet in orbit. If we try to imagine what terrestrial life would be like after 10 billion more years of evolution, we can start to understand that if life emerged in the early Universe, for example around the Methuselah Star or on the Genesis Planet, it would likely be completely unrecognisable to us. Also, we might realise that intelligent beings out there may have had this same idea some time ago – that it would be interesting to introduce life to nearby planets, to see what happens. It is not impossible that what I had just witnessed was really the subject of a much older life-seeding experiment here on Earth unwittingly presenting a proposal to run his own similar experiment elsewhere. There is a theory of the origins of life called panspermia, proposing that primordial life was delivered to Earth from space billions of years ago. But we're getting ahead of ourselves.

To explore beyond our Solar System, even remotely, will require new propulsion technology. At current maximum rocket speeds, it would take tens of thousands of years to get to the nearest exoplanet, Proxima Centauri. A revolution in physics and our understanding of spacetime will be required to realise interstellar travel, never mind visiting other galaxies, which are millions and millions of times further away. While the Universe is vast, luckily for us there are some rather interesting places that may shed light on our quest to understand our origins which are not so far from home.

Places we can observe: our Solar System

Our Sun is at the heart of things here in our Solar System. In the powerful gravity of our newly formed star, swirling masses of debris gathered gradually and often violently into the orbital bodies making up our System. In addition to its gravitational influence due to its mass – which makes up an impressive 99.8 percent of the total mass in our Solar System – the Sun's heat and light have enabled a fascinating range of events. Including, on at least one orbital body, the emergence of life.

Our Solar System is an island of activity in the vastness of interstellar space. Although it is our locale, so to speak, and relatively close – so much so that parts of it are visible to the naked eye – our knowledge of it is mostly inferred. For the vast majority of our time on Earth, we have been limited to observing the night sky from our vantage point on the surface of our planet, as well as picking up rocks that have fallen from space. Our first direct knowledge of any place other than Earth was through crewed visits to our Moon half a century ago. More recently, our progress in robotics and automation has opened up exciting avenues for learning about the Solar System via remote investigation, and we have brought back samples from the solar wind, both sides of the Moon, multiple asteroids and a comet for further analysis. While things get more extreme the further out we go – from our Earthly perspective at any rate – some worlds may yet hold surprises for us in our quest to understand the origins of life back home.

Earth is the only planet we know of to host liquid water on its surface; the oceans that cover most of it are one of its most striking features. Our oceans are abundant with life: just a drop of seawater can contain over a million different species of microorganisms. The search for water has driven much exploration in our System; both in terms of the possibility of finding life or evidence of life and the potential for establishing life beyond

Earth. In fact, this molecule so vital to terrestrial life has been detected in a range of other places in the Solar System, perhaps unsurprisingly, as hydrogen and oxygen (along with helium) are in the top three most abundant elements in the Universe. The abundance of the H_2O molecule in off-world locations in our Solar System is exciting in terms of understanding the history and future of life in our System, leading naturally to questions like: are these strange worlds places we could visit? Might we find clues to our origins, or even life there?

The Solar System is typically divided into two regions: the Outer System and the Inner System. Our direct knowledge of the Outer System is as limited as the faint sunlight there – only about one-thousandth of the light received by our planet reaches the furthest planet, Neptune. The icy outer reaches beyond Neptune are the last frontier of our System, potentially holding pristine clues to the origins of the planets and perhaps even ourselves (out here ice could be frozen water, methane, ammonia or other compounds). Though part of our System, it's easy to forget how little we know – still – of this furthest realm.

Neptune's existence was predicted in the 1840s by mathematician Urbain Le Verrier based on observations of the movements of the known planet Uranus. By analysing small perturbations in its orbit, Le Verrier concluded that an as yet undetected planet of a similar size to Uranus was orbiting just beyond it. On receiving a letter from Le Verrier, astronomer Johann Galle discovered Neptune that same night, at a location just a degree off from Le Verrier's prediction. Subsequent to this spectacular demonstration of the predictive power of theoretical physics, what lies beyond Neptune in the cold, dark expanse of the Outer System remained a mystery for almost a century.

Then, in 1930, further anomalies in the orbit of Uranus attracted the attention of astronomer Clyde Tombaugh. While Pluto may have been downgraded from planet status in 2006 by a committee reasoning that it had not yet cleared enough neighbouring objects to qualify, the story of Tombaugh's discovery of Pluto did end rather fantastically with him becoming the first person to visit it (posthumously, that is). Besides carrying Tombaugh's ashes to Pluto, the New Horizons mission to the Outer System in 2015 revealed that the dwarf planet has five moons, the largest being about half its size, a thin atmosphere of mostly nitrogen, methane and carbon monoxide. While average surface temperatures are below negative 230 degrees Celsius, surprisingly, Pluto's surface features indicate geological activity, which, coupled with potential internal radioactivity, may be sufficient to support a subsurface ocean. If sustainable so far from the Sun, what may lurk within these waters remains a compelling mystery.

Beyond Pluto, the existence of a belt of objects in the far reaches of the Outer System was predicted in the 1950s by astronomer Gerard Kuiper, and was finally detected in 1992 by astronomers Dave Jewitt and Jane Luu, who had been scanning the skies in search of dim objects beyond Neptune for years. The Kuiper Belt comprises a vast ring of millions of icy bodies glinting dimly in the light of the distant Sun. Far enough away to have avoided the gravitational pull towards the larger planets, these Kuiper Belt bodies are remnants of the early Solar System and can provide valuable insights into its origins. Some of them are also behaving strangely.

In spite of the discovery of a range of icy worlds at the edge of the Outer System, there remains an elephant in the room: the irregular motion of a group of Kuiper Belt objects could be indicative of a planet with a mass of as much as ten times that of the Earth, and an elongated orbit hundreds of times as far from the Sun as the Earth. And we've seen how such orbital anomalies have given rise to the prediction and detection of large celestial bodies in the past. Could it be that there is a ninth planet in the Solar System (sorry Pluto), bigger than Earth, that we've not yet noticed?

Author Zecharia Sitchin claims that Sumerian mythology refers to a planet called Nibiru going round our Sun with a highly elliptic orbit of 3,600 years extending from the Asteroid Belt to over ten times further from the Sun than the dwarf planet Pluto. Sitchin's planet is typically dismissed by arguments of orbital stability – such close encounters with the planets in the Inner System would result in dramatic changes to the proposed orbit within just a few revolutions. However, the fact that we have not been able to disprove the existence of an as yet undetected planet larger than our own orbiting our Sun leaves us to conclude that our knowledge of even our own Solar System is decidedly limited.

The distant body Farfarout (yes, discovered beyond the previously furthest known body Farout) remains, for now, the most distant catalogued Kuiper Belt object in the Outer System. Farfarout is a dwarf planet about 400 kilometres across and around 20 billion kilometres from the Sun; even light takes nearly twenty hours to reach it. These distant frozen worlds, largely untouched by the turbulence out of which the bodies closer to the Sun formed, contain the building materials for our System in their primary form. How this icy realm may yet contribute to our understanding of our System's origins, and perhaps our own, remains to be seen; the New Horizons mission currently in the Kuiper Belt is planned to be operational until the end of decade.

Moving a bit closer to home, some of the largest celestial bodies in our System are big and bright enough to be familiar features of our night sky. The nearer regions of the Outer Solar System are home to four giant planets that make up 99 percent of the mass of known objects orbiting the Sun. They are referred to as Jovian planets, after the largest of the four: Jupiter. More than ten times bigger than Earth and with gravity 2.5 times stronger, most of Jupiter's mass consists of hydrogen and helium. This means you would weigh more than double there than what you do on Earth, if there were any solid ground to stand on. Jupiter's gaseous surface surrounds an outer core likely of liquid metallic hydrogen producing its powerful magnetic field, and within that a dense inner core potentially of solid rock, metal and ice. Saturn is the second-largest planet in the Solar System, with a range of characteristics in common with Jupiter. Saturn's most famous feature is its ring system, its startling beauty having been captured in high resolution by the Cassini mission in 2017, just before the spacecraft's dramatic plunge into Saturn's atmosphere. The rings are mostly made up of ice particles, and also debris and dust, thought to be pieces of space rocks or even moons shattered by Saturn's powerful gravity before reaching the planet.

Slightly smaller than these two gas giants, the ice giants Uranus and Neptune are each around four times bigger than the Earth. Uranus' name refers to the Greek god of the sky, who according to mythology was the great-grandfather of Mars, the grandfather of Jupiter and father of Saturn. Uranus and Neptune are similar in composition to their larger siblings, with hydrogen-rich atmospheres below which is predominantly ice, thought to be made up of water, methane and ammonia, as well as rock. Uranus has the coldest atmosphere of all the planets in the Solar System, with a minimum temperature of negative 224 degrees Celsius. While the almost right-angled tilt of its equator to its orbital plane gives Uranus the most extreme seasons in the System, Neptune is home to some of the strongest winds, which reach speeds of over 2,000 kilometres per hour.

Jupiter, Saturn, Neptune and Uranus have surfaces of swirling gases; attempting to land on any of these gaseous and icy giants would result in being sucked down by a powerful gravitational field and then crushed by rapidly increasing pressure and density closer to their solid central cores. It's difficult to imagine what kind of life, if any, might originate in such foreign environments compared with what we are used to closer to the Sun. However, there are some worlds with surfaces in the Outer System that we might find more familiar: moons, hundreds of them, detected in orbit around the outer planets.

To support liquids on the surface of a celestial body, some kind of atmosphere is required. Titan, Saturn's largest moon and the second largest in the Solar System, is the only moon known to have a dense atmosphere, which, like Earth's, is made up of mostly nitrogen, also with small amounts of methane (though at a 50 percent higher pressure than ours). The opaque atmosphere prevented us from knowing much about the surface for a long time, until a lander was deployed from the Cassini mission to touch down there in 2005, revealing liquid lakes in the polar regions. Titan is the only known body besides Earth to have liquids on, as opposed to beneath, its surface. These liquids, however, are not water but hydrocarbons like methane and ethane, raining down from clouds and evaporating back up into the atmosphere at maximum temperatures of around negative 180 degrees Celsius. Beneath all this, Titan is also thought to have a subsurface ocean of liquid water and ammonia. Perhaps the Dragonfly mission, scheduled to depart from Earth later this decade and which will take seven years to reach Titan, will provide some answers.

The giant planets' huge masses, coupled with the highly elliptic orbits of some of their moons – meaning that these moons alternatively pass close to and also travel far from their planets during each orbit – result in powerful tidal forces that through friction may create enough heat to maintain liquid water beneath some moons' icy exteriors, even in the absence of a significant atmosphere. Some of these moons are also geologically active, and may contain radioactive material producing heat. From Pluto to the moons of the gas giants, there are in fact a range of subsurface environments in the Outer System where, even so far from the Sun, we believe there may be enough heat to support the presence of liquid water.

And in recent years, what appear to be plumes of water vapour have indeed been observed venting into space from the fissured crusts of both Jupiter's moon Europa and Saturn's moon Enceladus, revealing geological activity and potentially the presence of salty oceans below their frozen surfaces. Moreover, the precursors of amino acids, as well as phosphorous, necessary for life as we know it, were detected by Cassini in a vapour plume emitted by Enceladus in 2015. Ganymede, also