# SAMPLE

## The Elements

From Stars to You

Aira Astralis

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# Chapter 1: The Discovery of The Elements

The story begins with a question older than science: what, at bottom, is the world made of? The earliest answers we know of were philosophical rather than experimental, but they established a habit of thought that never left.

Before leaving the ancient world, one more tradition deserves its paragraph, because it is the East's contribution to the same question. Chinese natural philosophy organized matter into five phases, wuxing, wood, fire, earth, metal, and water, not as building blocks but as processes, a cycle of generations and conquests in which wood feeds fire, fire's ash is earth, earth bears metal, metal collects water, and water feeds wood. The scheme's purpose was practical, governing medicine's organs, seasons, and tastes, and its logic, matter as transformation rather than substance, is the closer ancestor of chemistry's actual behavior, in which elements combine and change; the West's static four held the schools, but the East's moving five was, in spirit, the better guess, and both belong in the elements' prehistory as the two ways humanity first tried to think its materials through.

The classical elements typically refer to earth, water, fire, and air, and (later) aether, which ancient natural philosophy proposed as the fundamental constituents of the physical world. Ancient cultures in Greece, Angola, Tibet, India, and Mali had similar lists, which sometimes excluded aether and sometimes added other categories: the Chinese system of five phases ran wood, fire, earth, metal, and water, organizing medicine, music, and statecraft alike, and the systems agree on one thing, that a small set of primal substances must underlie the endless variety of matter.

The Greek version became the ancestor of the West's idea. Some of these interpretations included atomism, the idea of very small, indivisible portions of matter, proposed by Leucippus and Democritus, alongside the more mainstream elemental theories. In Europe, the ancient Greek concept, devised by Empedocles, evolved into the systematic doctrine of the four classical elements that dominated for two millennia. Greek philosophers had debated which substance was the arche, the first principle or primary substance underlying everything: Thales argued for water, Anaximander for the boundless apeiron, and Heraclitus for fire, until Empedocles proposed that all four of the tangible elements were equally fundamental. He called them the four roots, rhizomata, and paired them with the forces of attraction and separation. Aristotle gave the scheme its lasting form, adding aether as the fifth element for the heavens, and the ancient Greek word for element, stoicheion, from a root meaning to line up, meant the smallest unit of a series, the letter of an alphabet: the metaphor, matter's letters, is the one this book still uses.

The doctrine's prestige was its problem: it explained everything, and so it could not be tested. An element, we take it, is a body into which other bodies may be analysed, present in them potentially or in effect, and indivisible in fact into other kinds of bodies: that, or something like it, is what all men in every case mean by element,

Aristotle wrote, and his definitions of the four elements as combinations of hot, cold, wet, and dry qualities, fire hot and dry, air hot and wet, water cold and wet, earth cold and dry, organized a classic diagram of nested squares whose corners carried the elements and sides the qualities, a picture that would dominate the schools for eighteen centuries.

The break with the classical doctrine began in the seventeenth century, and its author was a skeptical aristocrat with a furnace. One such version was provided by Robert Boyle in The Sceptical Chymist, published in 1661, which attacked both the Aristotelian four and the alchemists' three principles of salt, sulfur, and mercury: if you but consider a piece of green wood burning in a chimney, Boyle wrote, you will readily discern in the fire the flame, the smoke, and the liquor, and in the embers the ash and the remaining charcoal, a decomposition into more than the allowed elements, and from such observations he argued that the elements must be discovered by experiment rather than assumed by philosophy. The book did not settle what the elements were, but it settled what an element claim had to look like: evidence.

The eighteenth century supplied the evidence. Henry Cavendish isolated hydrogen in 1766 and Joseph Priestley oxygen in 1774, and Antoine Lavoisier, weighing everything before and after reaction, overturned the phlogiston theory and published in 1789 a list of thirty-three substances he could not decompose, the first modern attempt at a table of elements, honestly marked with the ones, light and caloric among them, that would later prove mistaken. The concept was now operational: an element is what analysis cannot divide. John Dalton, in 1803, gave the elements a quantitative soul, assigning each a characteristic atomic weight, and with the chemical revolution complete, the hunt for new elements became a profession: Humphry Davy used the new electric battery to tear soda and potash apart, discovering sodium and potassium in a single month of 1807, and by mid-century the list had grown past fifty, sorted by the new technique that read light itself.

That technique was spectroscopy, and it changed the hunt's rules. Each element, heated or excited, emits light at a signature set of sharp wavelengths, a fingerprint unique and unforgeable, and with the spectroscope the chemists could identify an element from a speck: cesium and rubidium were discovered in mineral-water residues by their blue and red lines in 1860-61, thallium by its green line, indium by its blue. The discovery of helium in 1868 was the method's triumph and promise, an element found in the Sun's spectrum during an eclipse before it was ever held in a hand on Earth, and the promise held: the technique founded modern astronomy's knowledge of the stars' contents, and it filled the last gaps in the terrestrial list before the century closed.

The spectroscopic era also produced the field's founding detective work, and it is worth retelling. The Sun's spectrum carried a yellow line near sodium's that matched no known element, and Lockyer named it for the Sun itself, helium, the sun-element, a discovery made on a theoretical limb that took twenty-seven years and a lava-heated ore to confirm on Earth; the same method later caught the coronium mistake, a line credited to a nonexistent element that turned out to be iron so highly charged it was

unknown to the lab, a lesson the field absorbed. Between the triumph and the mistake, spectroscopy taught the elements' science its modern humility: the sky's lines are elements' signatures, but reading them takes the whole laboratory's knowledge, and the universe is under no obligation to use only the known alphabet.

Helium's full biography deserves one more sentence, because it is the elements' most delayed gratification. Found in the Sun in 1868, found on Earth in a uranium ore's gas in 1895, understood as the second atom and the second element, it then spent a century being the chemistry's refusenik, the inert gas that liquefied at the lowest temperature of any element and became the cryogenic standard, and the modern decades have given it the shortage, the supply problem and the escape problem, a light atom the Earth cannot hold and the universe's second most abundant thing runs short on the one planet that needs it for magnets and machines. No element's story better shows the whole arc: a spectral line, a definition, a century of uses, and a future problem, all one element, all from two protons.

The twentieth century made the list itself a physics problem. When the atom's nucleus was opened, the definition of an element sharpened from an indecomposable substance to a proton count, every element one atomic number, and the hunt moved to the laboratory's accelerators and reactors: technetium in 1937 became the first element synthesized rather than dug up, and the elements beyond uranium followed, built one proton at a time, until the list stood complete to oganesson, element 118, officially named in 2016. The discovery of the elements, from bronze-age fires to the fusion of heavy ions, is thus the whole story of human analysis, each age finding the elements its instruments could reach.

The era's discovery of the neutron deserves its own sentence, because it completed the atom's census and explained the isotopes in one stroke. Chadwick's 1932 detection of the neutral particle, predicted by Rutherford's group as the nucleus's missing glue, gave the isotopes their explanation at last, differing neutron counts in the same proton-defined element, and gave the century its nuclear physics: the neutron, neither attracted nor repelled, could walk into any nucleus, and the neutron's walks made the artificial elements, the reactors, and the bomb. No other particle did so much to change the elements' meaning within one decade.

## Chapter 2: The Rare Earths' Labyrinth

The hardest hunt in the elements' history was not the hunt for the rarest or the heaviest but for a family of seventeen look-alikes, the rare earths, whose story deserves its own chapter because it is the discovery era's marathon and the modern economy's dependence wound into one thread. The lanthanides, the fifteen elements from lanthanum to lutetium, plus their two cousins scandium and yttrium, are chemically the closest family in the whole list: their atoms carry nearly identical outer electron architecture, and so nearly identical behavior, that telling them apart was for a century the discipline's cruellest puzzle, and solving it required a patience the rest of chemistry never needed.

The labyrinth began in one quarry. Ytterby, a village on the island of Resarö near Stockholm, gave the world a heavy black mineral from which Johan Gadolin, in 1794, extracted a new earth, yttria, and the village ended up with more elements named for it than any other place on Earth: yttrium, terbium, erbium, and ytterbium all carry the quarry's name, a postal address shared by four letters of the alphabet, and the mine, worked first for feldspar and quartz, has been called the most productive real estate in the history of chemistry, a hole in Swedish granite that filled four lines of the periodic table.

The century that followed was a comedy of fractions. Carl Gustaf Mosander, heating the new earths and leaching them one fraction at a time, found lanthanum in 1839 and, two years later, didymium, named for the twin because its spectrum doubled the lines of its supposed parent; the earths kept splitting under examination, terbia separating from erbia, each new earth proving a mixture, and the family's chemistry became a set of Chinese boxes in which every box, opened, contained a smaller box of the same kind. No other region of the list cost so much labor per letter: an element's discovery, elsewhere a paper, was here a decade.

The boxes' last layers were the twin's divorce and the family's feuds. In 1885 Carl Auer von Welsbach, working with the repetition chemistry of fractional crystallization, split didymium itself into two elements, praseodymium, the green twin, and neodymium, the new twin, and the impostor that had sat in the list for forty years quietly became two honest letters; samarium had already been named for samarskite, the mineral that carried it, itself named for a Russian mining official, the first element ever named for a person; europium, the last of the seventeen to be found, came in 1901; and the discovery of lutetium, in 1907, produced the family's finest priority fight, Urbain in Paris and Welsbach in Vienna each holding samples of the same new element with different names for it, an argument the international committees had to settle, and settled, as they later would for the superheavies, with history keeping both claimants' stories.

The labyrinth's solution came not from cleverness but from grinding repetition, and its difficulty deserves the book's most honest explanation. The family's members share the same outer electron structure, the chemical handshake by which atoms recognize one another, and so every reaction that separates two of them separates them only slightly, by margins that must be multiplied thousands of times: chemists of the classical era performed the same crystallization ten thousand times over to bring two adjacent lanthanides apart, a labor so maddening that the separations were compared to sorting a beach's grains of sand by shade. Only the ion-exchange techniques of the mid-twentieth century, which walk the atoms down an adsorbent column one subtle difference at a time, industrialized what the fractionalists had done by hand, and the family whose chemistry defeated chemistry for a century is now dispensed by the ton.

The modern payoff closes the arc. The rare in the family's name was always the least accurate label in the list, cerium being commoner in the crust than copper, and the difficulty was never abundance but concentration and separation; once industry learned to concentrate and separate, the look-alikes turned out to be the electronic

age's indispensable cast: neodymium for the strongest permanent magnets known, europium and terbium for the phosphors that light screens, yttrium for the lasers and superconductors, all of them elements the reader carries in a pocket. The labyrinth, entered two centuries ago for a quarry's black stone, exits into every device the modern world holds, and the family that cost chemistry its patience now underwrites its conveniences, the marathon's delayed and generous prize.

The family's edges deserve one more paragraph, because the cousins tell the prediction story. Scandium was eka-boron, the gap Mendeleev described in advance from his pattern's demands, and Lars Fredrik Nilson, finding it in 1879 in Scandinavian minerals, named it for Scandinavia, a predicted letter arriving with its address attached; yttrium, though it sits with the family chemically, is not a lanthanide at all, its electrons arranged differently, and the seventeen's loose membership, fifteen true lanthanides plus two adopted cousins, has confused exactly the generations of students the naming was meant to help.

## Chapter 3: Understanding The Elements

The modern understanding of an element is wonderfully simple to state: an element is a class of atoms, and what makes the class is a single number, the count of protons in the atom's nucleus. Every hydrogen atom has exactly one proton, every carbon atom six, every gold atom seventy-nine; the proton count, called the atomic number, fixes the positive charge of the nucleus, the charge fixes the arrangement of the electrons around it, and the electron arrangement fixes all of the element's chemistry. This is why the elements are the alphabet of matter: each letter is one number, and everything else about the element follows from that number the way a word's sound follows from its letters.

The proton count's power deserves one more example, the deepest in chemistry: it explains why the elements recur. Add one proton and the new element starts a fresh electron arrangement, add eight and the outer shell repeats its pattern, and the elements eight apart, lithium and sodium and potassium, are chemical siblings because their electron architecture rhymes, the same outer structure rebuilt at a larger scale. The whole periodic table, the entire pattern of the elements, is thus a consequence of one law, the positive nucleus and its negative cloud, counting upward, and the table's existence is the proton count's guarantee, which is why physics, having found the number, could hand chemistry its alphabet with confidence.

The definition's history is worth one more sentence, because it explains the periodic table's authority. When Moseley showed in 1913 that each element's X-ray spectrum jumped in step with an integer, the integer turned out to be the nuclear charge, and the century-old puzzle of why elements' atomic weights came in slightly irregular order, tellurium heavier than iodine yet chemically lighter, dissolved at a stroke: the order was the proton count, the weights were averages, and the table's arrangement, justified until then by chemistry's patterns alone, was anchored in the nucleus. An element, from 1913 on, is a number, and the number's sequence is the table's spine.

The atoms are not, however, all identical within an element. Atoms with the same number of protons but different numbers of neutrons are called isotopes, and the isotopes of an element are chemically the same, sharing every behavior that depends on electrons, while differing in mass and in nuclear stability. Carbon has three naturally occurring isotopes: all its atoms have six protons, but most have six neutrons as well, one in a hundred trillion carries eight, the famous carbon-14 whose slow decay dates the past, and the remainder carry seven. Some elements have no stable isotopes at all, and others have several; tin holds the record with ten, a stability so even that its ores are mined as the pure metal's graves.

The element as a substance is subtler still, because most elements do not exist in nature as loose atoms. With a few exceptions, the noble gases, which drift alone and complete, and a handful of metals, elemental substances are collections of atoms bonded to their own kind, and the same element can bond to itself in more than one arrangement. Carbon as diamond and carbon as graphite are the same element in different allotropes, one the hardest natural substance, the other a lubricant; oxygen as the breath gas and oxygen as ozone are the same element in different molecules; phosphorus, sulfur, and selenium likewise each come in forms so different that early chemists mistook them for separate elements. The element, strictly speaking, lives in the atom, and the substance you can hold is the element wearing one of its several possible dresses.

Allotropy's strangest cases deserve a list, because they show how far one element can stretch. Sulfur's rings and chains, a hundred-degree dance of molten red and brown, gave chemists the first pure elements to study as polymers; phosphorus comes as white, red, violet, and black, one fatal in the dark and one semiconducting, so different that only the atomic number says they are kin; and carbon's diamond and graphite, joined in modern decades by the fullerenes, the nanotubes, and graphene, are the same element as ember and as gem, the allotropy that launched nanotechnology. The lesson generalizes: an element is its atoms, but a substance is the atoms plus the arrangement, and the same number can wear many material characters.

Two further distinctions complete the understanding. First, an element is not a compound: compounds, water or rust or salt, are fixed combinations of two or more elements that can be decomposed, while an element cannot be broken into anything simpler by chemical means; the boundary is the definition of chemical, and the nuclear age added the honest footnote that the elements can be broken, by physics, into other elements, at energies no chemistry reaches. Second, the element is not the isotope: nuclear scientists work with nuclides, the full census of proton-neutron combinations, of which the elements are the sorted summary, and the distinction matters throughout this book, because an element's natural abundance, radioactivity, and usefulness in science often come down to which isotopes it contains.

## Chapter 4: Key Characteristics of The Elements

A few characteristics organize the whole cast. The first is the divide that runs through

the list between the natural and the synthetic: ninety-four elements are known to occur on Earth, from hydrogen up to plutonium, and the remaining twenty-four, americium through oganesson, exist only where they are made, in laboratories, though a few of the natural heavy elements are so rare that they, too, have never been seen outside an accelerator's targets. Among the natural elements, the abundances are wildly uneven, a pattern that is the book's constant background: hydrogen and helium, made in the universe's first minutes, are overwhelmingly the most common elements in existence; the next few, carbon, oxygen, neon, nitrogen, iron, are the ash of stellar furnaces; and everything past that, from iodine to gold to uranium, is the rare dust of rare catastrophes, present in the Earth's crust at parts per million or billion.

The second characteristic is the metals-and-nonmetals divide. Three-quarters of the elements are metals, lustrous, conducting, malleable stuffs that conduct electricity, and the nonmetals, a minority concentrated near the table's upper right, are everything else: the gases of breath and burn, the brittle solids of sulfur and iodine, the elements life is built from. Between the two runs the diagonal band of the metalloids, boron, silicon, germanium, arsenic, antimony, tellurium, which behave one way or the other depending on the company, and which the semiconductor industry has made the most consequential borderline in the modern economy; the border is genuinely fuzzy, with elements near it argued over by chemists to this day, and the fuzzy line is itself a characteristic of the list, that its categories are natural kinds with soft edges.

The metals' internal logic deserves a sentence, because their shared behavior is the easiest to explain of all the categories: metals hold their outer electrons loosely, in a sea that flows from atom to atom, and the sea is the shine, the conduction, and the malleability at once, electrons absorbing light, carrying current, and letting the positive cores slide without shattering. One structural fact, electrons unbound, thus generates a dozen familiar properties, and it is the same fact that makes metals the natural cast of electrical technology, from the copper in the wall to the lithium in the phone.

The nonmetals deserve their own sentence of wonder, because they are the minority that runs everything. Six nonmetals, the CHNOPS set of the biologists, are the whole of life; three more, oxygen itself, nitrogen, and argon, are the atmosphere; and the nonmetals' compounds with each other and with hydrogen, water, ammonia, methane, carbon dioxide, are the working fluids of the planet's chemistry. The metals get the machines, but the nonmetals get the machine of life, and the elements' most important divide, for the only readers who are alive, is the one that separates the cast of biology from the rest of the list.

The third characteristic is personality: the elements are not interchangeable ingredients but individual characters with habits, and chemistry's practical art is knowing their habits. The alkali metals, lithium through cesium, all shed an outer electron so eagerly that the heavier ones ignite on water; the halogens all reach for an extra electron so strongly that fluorine attacks nearly everything including glass; the

noble gases, complete-shelled and self-sufficient, refuse all chemistry until the twentieth century forced argon and xenon into a few compounds; and the transition metals, the table's broad middle, form the colored solutions, catalysts, steels, and magnets that industry lives on. Gold's refusal to tarnish, mercury's liquid strangeness, aluminum's lightness locked for decades in its stubborn ores: these are the individual habits, not the categories, and they are why a book about elements is inevitably a book of biographies.

The individual biographies could fill a library, and one more example earns its place: titanium. Its ores are common, its strength-to-weight the best of the structural metals, and its extraction so difficult, so jealous of oxygen, that the metal was a laboratory curiosity into the twentieth century, an aerospace dream until the cold war's metallurgy caught up, and the finish of every laptop and the frame of every hip joint now rides on the Kroll process and its stubborn successors. Titanium's story, an element abundant, superb, and nearly unusable until an industrial breakthrough, is the modern replay of aluminum's, and a reminder that the elements' usefulness is a history of processes, not just properties.

## Chapter 5: The Gases That Refused to React

The noble gases were found by a man weighing nitrogen, which is the elements' most accidental discovery and one of the discipline's best stories. In the early 1890s Lord Rayleigh, making precision measurements of the densities of gases, noticed that nitrogen drawn from the air was very slightly heavier than nitrogen made from chemicals, a discrepancy too small for most instruments of the day to have noticed and too large for an honest experimenter to ignore, and he published the puzzle in the journals instead of explaining it away, inviting the world's chemists to account for his thousandth-of-a-gram trouble.

The answer was a new element hiding in plain breath. William Ramsay, in 1894, swept the air's oxygen, water, and nitrogen away by chemical attack and found a stubborn residue, about one part in a hundred of the atmosphere, that refused every reaction, and the residue had its own spectrum, its own density, and its own indifference: argon, the lazy one, named in Greek for its refusal to work. Cavendish, a century earlier, had passed electric sparks through air and noted the same stubborn bubbles he could not consume, an observation that had waited a hundred years for its explanation, and Rayleigh's scales and Cavendish's sparks together gave the list a whole new character of matter, the gas that would not combine.

The family assembled itself within a decade, and its arrival embarrassed the table in the best way. Mendeleev's periodic law, the century's proudest pattern, had been built without any knowledge of the column: the inert gases fit no existing group, and their discovery forced the table to grow an entire new one, a zero column. Ramsay and Travers, in 1898, working with liquefied air and its fractions, found neon, the new one, krypton, the hidden one, and xenon, the stranger, three new elements in a single summer of patient distillation, and the family's membership closed on Earth when helium, already known from the Sun, was found in uranium ores, the column complete

decades before anyone could explain why it existed at all.

The explanation, and the family's one humiliation, came from quantum mechanics and from an accident. The inertness, it turned out, was completeness, an electron structure so satisfied that other atoms had nothing to offer it, a whole column of atoms with no wants; and in 1962 Neil Bartlett, studying the violently reactive platinum hexafluoride, noticed that it oxidized oxygen itself and tried the reagent on xenon directly, obtaining the first noble gas compound, xenon's forced entry into chemistry after sixty-seven years of refusal. A handful of xenon and krypton compounds followed, and radon's chemistry barely exists because its radioactivity outruns its reactions, but the family's rehabilitation was always narrow: the lazy gases can be made to work, briefly and under duress, and their refusal remains their character.

Their refusal is also their employment, which is the family's economic joke. Argon, too indifferent to react, fills light bulbs and welding shrouds, the gas you want precisely because it does nothing; neon, in Claude's sealed tubes from 1912, glows its famous red for a century of advertising, the element whose name means new becoming the symbol of the old-fashioned; krypton once defined the meter itself, its orange spectral line the world's ruler from 1960 until the meter's definition moved on in 1983; xenon anesthetizes without metabolism, flashes the camera, and propels spacecraft on ion engines of gentle, famous efficiency; and helium's cryogenic monopoly, the one use of the list that has no substitute, has already had its shortage told in these pages. The noble gases thus hold a unique position in the economy of the elements: they are bought for what they will not do, and their inertness, which cost them sixty-seven years of chemical anonymity, became in the twentieth century a product in itself.

One late footnote belongs to the family's strangest member, the one the reader cannot hold. Radon, discovered in 1900 as a radioactive emanation from radium, is the noble gas the periodic table did not want: a column of atoms defined by indifference, and one of them, the heaviest, defined by decay, its longest-lived form lasting days and its daughters scattering their own radiations through the lung. It was the last noble gas found and the only one first found by its radiation rather than its refusal, the family's rules catching an exception.

# Chapter 6: The Science Behind The Elements

The elements came before the planets. The science of where the elements come from, worked out across the twentieth century, is one of the great syntheses of physics and astronomy, and its outline belongs in any book about the elements, because the abundance pattern, the vast plenty of hydrogen and the microscopic scarcity of uranium, is not an accident but a history, readable in every rock and star.

A note on scale, because the abundance story deserves numbers. Hydrogen is about three-quarters of the universe's ordinary matter by mass and over ninety percent by count of atoms; helium nearly all the rest; every other element combined, the carbon and iron and gold and the ninety others, adds up to under two percent, and of that

two percent the lion's share is oxygen, carbon, neon, and iron, the stellar ashes. The Earth, born from dust already enriched by dead stars, is thus a redistribution, a planet of the rare stuff: hydrogen, the universe's commonest thing, is a trace gas in our air, and helium, the second commonest, had to be hunted for in the ground, a reminder that our world is not a sample of the cosmos but a sorted corner of it.

The first elements were made in the universe's opening minutes, in the hot dense aftermath of the big bang: protons and neutrons fused into nuclei in the first quarter-hour, and when the cooling stopped the reaction, the universe's inventory was roughly three-quarters hydrogen and one-quarter helium by mass, with traces of lithium and nothing else. Every other element, the carbon of every cell and the iron of every core, was made later, in stars, and the story of their manufacture is the subject of this series' volume on stellar nucleosynthesis; in summary, stars fuse the light elements into heavier ones for fuel, carbon and oxygen in ordinary stars, and iron at the end of the line, the most tightly bound nucleus, where fusion's economy stops.

The big bang's own inventory deserves its own sentence, because its poorness is the clue. The early universe was a fusion reactor that ran for a quarter of an hour and shut down: the expansion cooled the broth faster than the reaction could climb the ladder, and the nucleosynthesis stalled at lithium, leaving no carbon, no oxygen, no iron, nothing of what planets and people need. Every heavier element is thus, necessarily, second-hand, made inside stars that formed later, and the old picture of the elements as eternal stuff gives way to the modern one, an evolving inventory, with hydrogen the inheritance and everything else the earnings.

One last abundance number belongs here, because it explains the book's most quotable fact. The universe's ordinary matter, all the stars and gas and planets together, is roughly three-quarters hydrogen by mass, and the hydrogen was all made in the first minutes, so the most common element is also the oldest substance in existence, the atom every other atom was built from and the fuel the stars still run on. When the last stars have burned and the galaxies have dimmed, the universe's ledger will still be mostly hydrogen, unspent fuel in a dark tank, and the elements' entire story, from the first fusion to the last superheavy synthesis, is thus an episode in the middle of a much longer hydrogen age.

The elements beyond iron are the bonus of catastrophe. Fusion past iron consumes energy rather than releasing it, so the heavy elements are made instead by adding neutrons, in the slow simmer of aging stars and, more powerfully, in the seconds of a supernova's collapse and the collision of neutron stars, where neutron fluxes are so intense that nuclei fatten faster than they can decay, ratcheting up to gold, uranium, and beyond. The gold in a wedding ring is, quite literally, the residue of a neutron star collision or a dying star's explosion, dust from events that seeded the nebula from which the Sun and its planets condensed, four and a half billion years ago, and the same dust, sorted by the young Earth's melting, sank its iron to the core and stranded its rarer metals in the thin crust we now mine.

Radioactivity is the final piece of the science, and it explains the list's live edge. The heavier an element's nucleus, the harder it is to hold together, and beyond lead and

# ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.