SAMPLE

The Elements

From Stars to You

Aira Astralis

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Conclusion

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Introduction

Everything you have ever touched, breathed, or been made of is a combination of a little over ninety natural substances called the chemical elements. Iron and oxygen, carbon and gold, the calcium in bone and the sodium in salt: the elements are matter's alphabet, the short list of pure substances from which every material thing in the universe is assembled, and the story of discovering them is, in a real sense, the story of humanity learning what the world is made of.

The number deserves a moment's respect before the story starts. Ninety- four elements occur naturally, and perhaps half that number, twenty to thirty of the lightest and commonest, run essentially everything: the oceans, the atmosphere, the biosphere, and the bulk of industry are worked by fewer than thirty of the ninety-four, while the rest, from silver to uranium, are supporting players whose rarity is their value. The full list of one hundred eighteen, with the laboratory-made additions, is thus a census of two populations at once, the working majority and the exotic minority, and this book will keep both in view, because the minority's stories, the gold, the radium, the technetium, are where the elements' history is most dramatic.

The list itself has a strange history. Ancient thinkers knew a handful of metals and a few other substances, but had no concept of what made an element elemental, and for two thousand years the accepted answer was a philosophical guess, that everything reduced to earth, water, air, and fire. The modern definition, an element is a substance whose atoms all share the same number of protons, only became possible in the twentieth century, after the atom itself had been opened. Between the guess and the definition lie the great chapters of chemistry: the age of fire and metallurgy, the alchemists' stubborn centuries, the quiet revolution that weighed and measured the elements into a science, and the century-long hunt that filled the list from hydrogen to oganesson, the last natural element supplemented by twenty-odd made in laboratories.

This book is the story of the elements themselves: what they are, where they came from, how they were found, and why their properties make them the cast of every chemical tale. Their organization into the periodic table is a story of its own, told in a companion volume of this series; here the table appears only as the elements' address book, the map of the territory this book walks.

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.

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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.