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Excerpt
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PART I

Historical

they ate the oxen of the sun,
the herd of Hélios Hypérion

Homer, The Odyssey
(translation by Mandelbaum)

The history of understanding structure in our Universe is older than the story of Odysseus, and has as many twists and turns. Few of these paths remain familiar to most astronomers today, so in the early chapters I have simply collected some essential developments along the way. They are not without surprises. One of which is that many ideas now thought to be novel have really been known for tens, or hundreds, of years. Often they were no more than speculations, but sometimes they captured reality's core.

1

Cosmogony Myths and Primitive Notions

To every thing there is a season,
and a time to every purpose under heaven.
Ecclesiastes 3:1

Structure may be the most surprising property of our Universe. Structure differentiates things, and the changing of things introduces the notion of time. We can easily imagine universes without macroscopic structure, filled by an equilibrium distribution of matter and radiation: homogeneous, isotropic, and dull. Indeed such a state may have described our own Universe until fairly recently. The oldest structures we know are the high-redshift galaxies and quasars, dating from an epoch when the Universe was only about ten times smaller than it is now. Compare this with the epoch of decoupling of matter and radiation when the scale of the Universe was a thousand times smaller than now, with the epoch of nucleosynthesis at which helium formed when the Universe was a billion times smaller, and with the almost mythical quantum epoch when the Universe was more than 10^{50} times smaller.

Although the structure we now see may be considered fairly recent when viewed in terms of the expanding scale of the Universe, it is very old in terms of total time elapsed since the expansion began. This is because the relative rate of expansion of the scale of the Universe, $\dot{R}(t)/R(t)$, slows down as the Universe expands. In typical conventional cosmological models, the distance of the farthest galaxies and quasars corresponds to more than 90% of the age of the Universe since the big bang. Earlier structure no doubt existed, but our knowledge of it is much more uncertain.

Long before people knew the age and size of any astronomical structure, civilizations imagined many origins for the Earth and the Moon, the Sun and the stars. These cosmogony myths varied widely among different cultures, and sometimes rival myths arose within the same culture. Most of these myths begin with a magnified version of the locally familiar – rocks, oceans, personified gods with human vices, a giant clam, even a mirror world beyond the sky. Such basic elements, like some aspects of modern cosmology, had no origin themselves and were subject to no further questioning. Eventually there occurred a split, disruption, battle, or sexual union from which the Earth, Moon, Sun, oceans, sky, remaining gods, first people, plants, and animals emerge in assorted ways and combinations for each different myth. In several myths a cosmic egg forms or is produced. Something breaks it, or it opens spontaneously, and the structure of the universe emerges. Putting everything in its place, however, may require further work by the gods.

Cosmogony myths are usually grouped into historical or anthropological categories. But here, to emphasize their range, I suggest a thematic classification whose sequence tends toward increasing abstraction. Some examples represent each type and illustrate how many types contain common features. Naturally we view these myths and early cosmogonies through the lens of modern understanding. Any claim to decant the detailed attitudes of their original believers from our own concepts of the Universe would be largely illusory.

In the first group of myths, battles among the gods generate structure. Among the oldest is the Babylonian Epic of the Creation whose earliest known written tablets go back three thousand years and are probably based on still older versions. Not surprisingly, the Universe was organized by the god of Babylon himself, Marduk. He was the grandson of Apsu and Tiamet who personified the sweet and salt waters, from whose mingling was born a family of gods. They squabbled long and noisily, giving each other insomnia and indigestion, until Apsu and Tiamet disagreed over whether they should destroy their own progeny. Battle lines were drawn. Marduk, potentially the bravest, was selected king of the gods. He killed Tiamet by commanding the tempests and hurricanes to blow her full of wind until she was so puffed up she could not close her mouth. Then he shot an arrow into her heart and split her body into two halves, one forming the heavens and the other forming the Earth. After that it was relatively easy to organize the world, install the stars, fix the planetary orbits, and create humanity to do the hard work and leave the gods free to amuse themselves.

The old Greek version of the separation of Heaven and Earth is told by Hesoid (ca. 800 B.C.; see also Lang, 1884). His *Theogony*, an extensive geneology of three hundred gods, may derive its style partly from the earlier Babylonian epic, although this is unclear. It starts with Chaos, not in the sense of turbulence and erratic unpredictable motion we use today, but in the earlier sense of a vast formless dark chasm or void. Chaos was not a god, but a sort of principle, which produced the Earth (Gaia), underworld (Tartara), and love (Eros) gods. Earth bore Heaven (Uranus), then together they produced a bunch of nasty children, including Kronos whom Gaia encouraged to castrate Uranus. Thus Earth and Heaven were separated and a slew of other gods, nymphs, and giants developed from the bits and pieces of the wound.

Alternatively, according to the myths of Iceland, ice played a major role in the formation of the world from the void. One part of the void developed a region of clouds and shadows, another a region of fire, a third a fountain from which flowed rivers of ice. As some of this ice melted, Ymir, a giant who looked like a man, emerged, and then a giant cow to feed him along with other giants and giant men and women. These bore three gods who battled the giants, killing Ymir. His flesh became the land, his blood the sea, his bones the mountains, his hair the trees, and his empty skull the sky. Stray sparks from the region of the fire were placed in his skull by the gods to form the Moon, Sun, and stars, which were then set in motion. Maggots forming in Ymir's rotting corpse were made into the dwarfs of the underworld. Eventually the gods made humans from tree trunks.

A more abstract battle cosmogony was developed by the ancient Persians, especially the Zoroastrians. Two personifications, good (Ormazd) and evil (Ahriman), alternately created the opposing aspects of the world: light – darkness, life – death, truth – falsehood, summer – winter, pretty birds – biting insects, and so on for three thousand years. After another six thousand years Ormazd would win and the world would be purified. Observations can therefore put an upper limit on the age of this cosmogony.

In the second group of myths, the gods generate structure much more peacefully. In Genesis this is done by monotheistic decree rather than by magnifying tribal or family strife. First, light is created in the dark void, then the heaven and Earth are separated and heaven supplied with the Sun, Moon, and stars. In contrast, Japanese creation myths (perhaps partly derived from Chinese sources) began with three gods forming spontaneously in heaven who then hid themselves away. The Earth, which was first like a huge globule of oil floating on a vast sea, gave rise to two further hiding gods, and then seven generations of more normal gods. Izanagi and his wife Izanami, the last of these generations, caused the Earth to solidify by poking it with a spear given to them by other gods. They stood on the floating bridge of heaven during this process and a drop falling as they lifted up the spear formed the island of Onokoro, on which they landed. Their subsequent union gave birth to the rest of the Japanese islands (after some misbirths caused by the woman speaking first to the man, rather than waiting until she was spoken to) and then to a new range of nature gods. Izanami died in childbirth when the fire god was born and went to hell, where the distraught Izanagi followed trying to convince her to return. He failed, and after several misadventures returned to the surface where he cleansed himself by bathing in the sea and producing more gods. The greatest of these was the Sun goddess, Amaterasu, who resulted from Izanagi washing his left eye; the moon goddess, Tsukiyomi, came from washing his right eye. Thus were the Earth, Sun, and Moon created without the need for great battles.

The Pawnee Indians of Nebraska also had a peaceful cosmogony generated by decree. Their chief god, Tirawa, first placed the Sun in the east, and the Moon and the evening star in the west, the pole star in the north, and the Star of Death in the south. Four other stars between each of these supported the sky. He assembled the lightning, thunder, clouds, and winds creating a great dark storm. Dropping a pebble he caused the thick clouds to open revealing vast waters. Then Tirawa ordered the four star gods holding up heaven to smite the waters with maces, and lo the waters parted and Earth became manifest. Next he ordered the four star gods to sing and praise the creation of Earth, whence another huge storm rose up gouging out mountains and valleys. Three times more the gods sang and there came forth forests and prairies, flowing rivers, and seeds that grow. The first human chief was born to the Sun and the Moon, the first woman to the morning and evening star. The rest of humanity was created by the union of stars.

The third group of myths are less anthropomorphic animal cosmogonies. Islanders on Nauru, in the South Pacific, say that in the beginning only an Old-Spider floated above the primordial sea. One day she discovered a giant clam and looked in vain for a hole to enter by. So she tapped the clam. It sounded hollow and empty. With the aid of a magic incantation she opened the shell a bit and crawled inside where it was cramped and dark. Eventually, after a long search throughout the clam, Old-Spider found a snail. Although the snail was useless in its original form, she give it great power by sleeping with it under one of her arms for three days. Releasing the snail, she explored some more and found another, bigger snail, which got the same treatment. Politely, Old-Spider asked the newly energized first snail to open the clam a little wider to give them more room. As its reward, she turned the snail into the Moon. By the feeble light of the Moon, Old-Spider next found an enormous worm. Stronger than the snail, the worm raised the shell a little higher as the salty sweat poured from its body to form the sea. Higher still and higher he raised the upper half-shell until it became the sky. But the effort was too much, and the worm died of exhaustion. Old-Spider turned the second snail into the Sun near the lower half-shell, which formed the Earth.

Egg cosmogonies are the fourth group of myths. Present in the early Egyptian and Phoenician creation stories, they became especially prominent in the Greek Orphic and Indian Vedic cosmogonies. Followers of Orpheus believed that Ether, the spirit of the finite, gradually organized the cosmic matter into an enormous egg. Its shell was night, its upper part was the sky, and its lower part the Earth. Light, the first being, was born in its center and, combining with Night, created Heaven and Earth. In the Vedic cosmogonies, a golden egg arose and the Universe and all its contents were nascent within. After a thousand years the egg opened and Brahma emerged to begin organizing the Universe, first becoming a wild boar to raise the Earth above the waters.

A Finno–Ugric multi-egg cosmogony begins with the Daughter of Nature, Luonnotar, who grew bored of floating through the sky and descended to the sea where she lay amidst the waves for seven centuries. A large bird wanting to build a nest spied her knee sticking out of the sea. So the bird laid eggs there and sat on them for three days, until Luonnotar became irritated and flung them off. When they cracked open their lower parts combined to form the Earth, their upper parts became heaven, their yolks became the Sun, their whites the Moon, and the spotted bits formed the stars.

The fifth group of myths have inanimate origins. Sometimes, as with the primordial Egyptian concept of Nun it is the ocean that gives rise even to the gods. Elsewhere, as in Samoa, the Universe began as a series of rocks, first the rocks of heaven and then those of Earth. The Hawaiians had a myth in which the Universe was cyclic, each world emerging from the wreck of a previous one.

The sixth, most abstract, group of myths do not involve gods at all. Structure in these universes is completely self-generating. On the Marquesas Islands in the South Pacific is a myth that describes how "the primeval void started a swelling, a whirling, a vague growth, a boiling, a swallowing; there came out an infinite number of supports or posts, the big and the little, the long and the short, the hooked and the curved, and above all there emerged the solid Foundation, space and light, and innumerable rocks" (Luquet, 1959). This is not far from some modern cosmologies if we substitute "vacuum" for "void," "perturbations" for "supports or posts," and "galaxies" for "rocks." This last substitution signifies the scale over which people are aware of their surroundings. Essentially this is an evolutionary, rather than a theistic or geneological, view of the organization of the Universe. In common with almost all creation myths, darkness precedes light.

Gradually the early Greek philosopher-physicists replaced earlier creation myths with speculative attempts at rational explanations for the structure they knew. Ionians, typified by Thales of Miletus (about the sixth century B.C.), began this process by claiming that all natural things came into being from other natural things. The substance persists but its qualities change – a sort of conservation law – according to Aristotle's later description (*Metaphysics*). For Thales, water was the primitive element and he may have thought (though this is uncertain) that the Earth originated from water and continued to float on it. Suggestions (Kirk et al., 1983) for Thales's choice of water range from the influence of earlier Egyptian and Babylonian myths to the observation that corpses dry out.

Anaximander favored fire. Writing about the same time as Thales, he states (in the description of Hippolytus, the Roman theologian; Kirk et al., p. 135): "The heavenly bodies came into being as a circle of fire separated off from the fire in the world, and enclosed by air. There are breathing-holes, certain pipe-like passages, at which the heavenly bodies show themselves; accordingly eclipses occur when the breathing holes are blocked up." Thus cosmology continued its tradition of being often in error, but never in doubt.

More modern views emerged a century later as Leucippus and Democritus began to develop the implications of their atomic ideas. Since Leucippus thought there were an infinite number of atoms, it followed that there could be an infinite number of worlds.

> The worlds come into being as follows: many bodies of all sorts of shapes move "by abscission from the infinite" into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate apart, like to like. But when their multitude prevents them from rotating any longer in equilibrium, those that are fine go out towards the surrounding void, as if sifted, while the rest "abide together" and, becoming entangled, unite their motions and make a first spherical structure.

So far, this sounds a bit like gravitational clustering, but then he continues more fancifully:

> This structure stands apart like a "membrane" which contains in itself all kinds of bodies; and as they whirl around owing to the resistance of the middle, the surrounding membrane becomes thin, while contiguous atoms keep flowing together owing to contact with the whirl. So the earth came into being, the atoms that had been borne to the middle abiding together there. Again the containing membrane is itself increased, owing to the attraction of bodies outside; as it moves around in the whirl it takes in anything it touches. Some of these bodies that get entangled form a structure that is at first moist and muddy, but as they revolve with the whirl of the whole they dry out and then ignite to form the substance of the heavenly bodies. (Leucippus' theory described by Diogenes Laertius, a Roman biographer of the third century A.D., in Kirk et al., p. 417)

Thus the Universe is structured by natural, but ad hoc and unexplained causes. That the atomists thought in terms of short-range, rather than long-range, causes is suggested by Simplicius, the Roman Neoplatonist commentator describing their views in the sixth century A.D., a thousand years later: ". . . these atoms move in the infinite void, separate one from the other and differing in shapes, sizes, position and arrangement; overtaking each other they collide, and some are shaken away in any chance direction, while others, becoming intertwined one with another according to the congruity of their shapes, sizes, positions and arrangements, stay together and so effect the coming into being of compound bodies" (Kirk et al., p. 426).

This atomic clustering theory coexisted with the more continuum view of Diogenes of Appolonia. Since Thales and Anaximander had suggested water and fire, it was left to Diogenes to posit air as the fundamental element of cosmogony: ". . . the whole was in motion, and became rare in some places and dense in others; where the dense ran together centripetally it made the earth, and so the rest by the same method, while the lightest parts took the upper position and produced the sun" (Plutarch, second century A.D. in Kirk et al., p. 445). Diogenes may also have been the first to suggest that the Universe contains dark matter, an extrapolation from the fall of a large meteorite in Aegospotami (467 B.C.).

Plato and Aristotle, founders of the Academy and the Peripatetic schools, were next to dominate philosophy for a hundred years, fall into decline, and then be revived by the Romans and preserved by the Arabs until in the thirteenth century they became supreme authorities for four hundred years of scholastic church commentary. Alive, they stimulated science, but as dead authorities they were stultifying. Both of them abandoned the atomistic view that the Universe was infinite. Plato, in his "Timaeus" proposed that the Universe is analogous to a single unique living being (in his world of ideal forms), created by a good and ideal god as a model of himself. He made it spherical because it had no need of protuberances for sight, hearing, or motion. The Moon, Sun, and Planets were the first living gods, created to move around the Earth in ideal circles so they could define and preserve Time. Aristotle attempted to give somewhat more physical explanations. For example, in his "On the Heavens" the Earth is spherical because each of its parts has weight until it reaches the center. When Earth formed, all its parts sought the center, their natural place of rest. This convergence produces an object similar on all sides: a sphere. Here is one of the first physical arguments using local symmetry. Aristotle then goes on to cite two observations in support of a spherical Earth: the convex boundary of lunar eclipses and the changing positions of the stars as seen from different countries. He mentions the result of mathematicians who used this second method to determine the Earth's circumference; they found about twice the modern value.

Aristotle's arguments for a finite world and a unique Earth were less satisfactory. First he claims there are two simple types of motion, straight and circular. All others are compounds of these. Simple bodies should follow simple motions. Circular motion, being complete, is prior to rectilinear motion and therefore simple prior bodies like planets and stars should follow it. Next he says that only finite bodies can move in a circle, and since we see the heaven revolving in a circle it must be finite. Finally, the world is unique. For if there were more than one, simple bodies like earth and fire would tend to move toward or away from the center of their world. But since these bodies have the same natures wherever they are, they would all have to move to the same center, implying there could only be one world around this center.

During the temporary three hundred year decline of the Academic school following the death of Aristotle in 322 B.C., atomism resurged. It was carried to new heights by the Epicurians, culminating in its great exposition by the Roman poet Lucretius in the middle of the first century B.C.

Epicurus argued for an infinite Universe filled with an infinite number of bodies (atoms). "For if the void were infinite but the bodies finite, the bodies would not remain anywhere but would be travelling scattered all over the infinite void, for lack of the bodies which support and marshal them by buffeting. And if the void were finite, the infinite bodies would not have anywhere to be" (Long & Sedley, 1987, p. 44). Moreover, an infinite number of atoms could produce an infinite number of worlds where a world contained an earth, celestial bodies, and all the observable phenomena. This was necessary because if, as in the Epicurian philosophy, structure results by chance and not from teleology, the probability that our actual world forms will increase dramatically if an infinite number of worlds are possible. ". . . we must suppose that the worlds and every limited compound which bears a close resemblance to the things we see, has come into being from the infinite: all these things, the larger and the smaller alike, have been separated off from it as a result of individual entanglements. And all disintegrate again, some faster some slower, and through differing kinds of courses" (Long & Sedley, p. 57).

Rival Stoic philosophers who believed in a fiery continuum and a finite world surrounded by an infinite void scoffed at the atheistic Epicurian view. Indeed, Cicero, in his dialogs of the first century B.C., which translated the Greek views into Latin, has his Stoic spokesman say:

> Does it not deserve amazement on my part that there should be anyone who can persuade himself that certain solid and invisible bodies travel through the force of their own weight and that by an accidental combination of those bodies a world of the utmost splendour and beauty is created? I do not see why the person who supposes this can happen does not also believe it possible that if countless exemplars of the twenty-one letters, in gold or any other material you like, were thrown into a container then shaken out onto the ground, they might form a readable copy of the *Annals* of Ennius. I'm not sure that luck could manage this even to the extent of a single line! (Long & Sedley, p. 328)

This may have been one of the earliest probability arguments about the formation of world structure. Related arguments dominate much of the present discussion on the subject, as we shall see.

But it was Lucretius, writing about the same time as Cicero, who came closest to some ideas of modern cosmogony. The atoms of the Universe are constantly in motion. Those whose shapes interweave and stick together form dense aggregates like stone or iron. The less dense atoms recoil and rebound (we would call it elastic scattering) over great distances to provide the thin air; some atoms do not join at all but wander everlastingly through the void. To create collisions that produce structure, Lucretius introduces the idea of swerve:

> On this topic, another thing I want you to know is this. When bodies are being borne by their own weight straight down through the void, at quite uncertain times and places they veer a little from their course, just enough to be called a change of motion. If they did not have this tendency to swerve, everything would be falling downward like raindrops through the depths of the void, and collisions and impacts among the primary bodies would not have arisen, with the result that nature would never have created anything. (Long & Sedley, p. 49)

He almost seems to be portraying gravitational deflection. But then Lucretius gets muddled up by the idea that everything must move at the same speed through the unresisting void, independent of its weight. Swerve must occur by just a minimum amount, so it cannot be seen. And so the idea dissolves into an ad hoc hypothesis to save the scheme.

Nevertheless, his scheme gave rise to a statistical argument often used today: "For so many primary particles have for an infinity of time past been propelled in manifold ways by impacts and by their own weight, and have habitually travelled, combined in all possible ways, and tried out everything that their union could create, that it is not surprising if they have also fallen into arrangements, and arrived at patterns of motion, like those repeatedly enacted by this present world" (Long & Sedley, p. 59). This is his rejoinder to Cicero's Stoic.

Lucretius' most remarkable reason for believing that the Universe was indeed infinite was to consider the difference this would make to the large-scale distribution of matter.

> Besides, if the totality of room in the whole universe were enclosed by a fixed frontier on all sides, and were finite, by now the whole stock of matter would through its solid weight have accumulated from everywhere all the way to the bottom, and nothing could happen beneath the sky's canopy, nor indeed could the sky or sunlight exist at all, since all matter would be lying in a heap, having been sinking since infinite time past. But as it is the primary bodies are clearly never allowed to come to rest, because there is no absolute bottom at which they might be able to accumulate and take up residence. At all times all things are going on in constant motion everywhere, and underneath there is a supply of particles of matter which have been travelling from infinity. (Long & Sedley, p. 45)

At last in this brief sketch of nearly two dozen cosmogonies we have found one that contains the seeds both of a rational explanation and of a result that we can put into modern terms. But this seed fell on infertile soil, for it was to take more than seventeen hundred years before Isaac Newton added the motive force of gravitation.

2

First Qualitative Physics:

The Newton–Bentley Exchange

The aim of argument, or of discussion,
should not be victory, but progress.
Joseph Joubert, Pensées

Isaac Newton needs no introduction.

Richard Bentley was one of England's leading theologians, with strong scientific interests and very worldly ambitions. Eventually he became Master of Trinity College, Cambridge, reigning for forty-two contentious years. Tyrannical and overbearing, Bentley tried to reform the College (as well as the University Press) and spent much of the College's income on new buildings, including a small observatory. To balance the College accounts he reduced its payments to less active Fellows, while increasing his own stipend. After ten years of this, some of the Fellows rebelled and appealed to the Bishop of Ely and Queen Anne, the ultimate College authorities, to eject Bentley from the mastership. Various ruses enabled Bentley to put off the trial for another four years. Finally the Bishop condemned Bentley in a public court. But before he could formally deprive Bentley of his mastership, the Bishop caught a chill and died. Queen Anne died the next day. Bentley now put his theological talents to work to convince his opponents that he had won "victory" by divine intervention. So he retained the mastership and raised his salary still higher. Some years later, another attempt to expel him by a fresh Bishop also failed, and he remained Master until dying in 1742 at the age of eighty. During the crucial period of these collegiate upheavals, about 1708–1713, Bentley had Newton's firm support; simultaneously he was seeing the second edition of Newton's *Principia* through the University Press.

As a young man Bentley was asked, possibly through Newton's maneuvering, to give the first Robert Boyle lectures. Although now mainly known for his result that the pressure of a perfect gas is linearly proportional to its density at constant temperature, Boyle also left an endowment for lectures in defense of religion. Earlier, Bentley had studied much of the *Principia*, having obtained a list of preliminary readings in mathematics and astronomy from Newton. By late 1692, he had a few questions to ask Newton as he prepared the final manuscript of his eight Boyle Lectures.

These lectures were supposed to confute atheists and show that Natural Science still required a role for the Creator. In modern terms, the role that emerged was to provide initial conditions, boundary conditions, and divine interventions to account for those aspects of the Universe that could not be understood with the physics of Newton's day. Among other questions, Bentley asked why some matter in the Universe formed the luminous Sun and other matter became the dark planets, whether the motions of the planets could arise from natural causes, whether the lower densities