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# THE GREEK THEORY OF THE INFINITE UNIVERSE

By David J. Furley*

The picture of the world that was passed on by the classical civilizations to medieval Christian Europe was largely the work of Plato and Aristotle, with finishing touches from Ptolemy. It was a picture of a spherical world, with earth at the centre, motionless, and the stars wheeling round it at the circumference. Outside the sphere, there was either nothing at all, as Aristotle believed, or nothing of any interest. It was not until the sixteenth and seventeenth centuries that the picture changed comprehensively—a change that is accurately captured by the title of Alexander Koyré's book, *From the Closed World to the Infinite Universe*.[1]

Of course, the theory of the infinite universe was already anticipated in classical antiquity, in some of its essentials. But the classical theory was not the same as the one that displaced Aristotle in the seventeenth century. In particular, I believe the motivation was different, and I think the motivation of the classical theory could bear closer study. What did its proponents expect to get from the theory? What reasons did they have for holding it?

Let us begin with what seems obvious.

If we walk outside on a clear night, and then stop, and observe the position of the stars several times during the night, then two things may seem to us to be undeniable: first, that when we stop, then we are no longer moving but at rest; second, that the stars (except one, the Pole Star, perhaps) are moving, on arcs of circles. With just a little persistence and measurement, we work out that all the circles on which the stars move have their centre on the line that passes from the one stationary point, at the Pole, through the earth. And with an effort of imagination, because all the stars except a handful always keep fixed positions relative to each other, we conclude that these circles are not independent rings, but are all joined together on the surface of a great sphere, which rotates as a whole once a day.

From these apparently plain observations and this one immensely plausible inference, it follows that the size of the world must be limited. The whole sphere carrying the fixed stars completes a 360°

* The following is a version of a lecture given at the Triennial Meeting of the Hellenic and Roman societies and the Classical Association of Great Britain at Cambridge in August 1978.

[1] Baltimore and London, 1957; rpt. 1968.

rotation around its axis in 24 hours. If we imagine the radius of the sphere to increase, we must imagine the speed of motion of the stars to increase proportionately. And if the radius increases to infinity, so does the speed. Aristotle produced a neat set of arguments, in *De caelo* I, to show that if the stars move round the earth they cannot be *infinitely* distant from the earth. (De Caelo, I, 5, 271 b 28 ff.)

So long as it is accepted, then, that the earth is at rest and the stars move, it must also be accepted that the world is a limited system, a very important fact to remember when we speak about Greek theories of the infinite. There is a difference in this respect between the Greek theory and the theory that has been held since the seventeenth century. Today, we can think of ourselves as being somewhere in the middle of a vast forest of stars, so to speak, that stretches interminably away in every direction. We can see some of the stars with the naked eye, and we believe some are comparatively close, and others further away. We know that telescopes will bring more stars into view—stars that were invisible to the naked eye not merely because they were too small or too dim to be seen, but also because they were too distant. So we come to think that what we see is the nearest region of a starscape that would continue indefinitely for as long as we could move our viewpoint further and further into it.

Greek theories of the infinite universe, however, present a significantly different picture. What they saw in the night sky was not the beginning of the infinite universe: it was rather the boundary beyond which the infinite universe began. This point stands out clearly enough in the most famous classical description of the infinite universe:

> ergo vivida vis animi pervicit, et extra
> processit longe flammantia moenia mundi,
> atque omne immensum peragravit mente animoque.
>
> Lucretius, *De rerum natura,* I, 73-75[2]

So Lucretius praises the achievement of Epicurus. His mind was powerful enough to range "beyond the fiery ramparts of the world" into the boundless universe. The world is like a walled city with unknown country outside the walls.

Notice that this picture was even stamped on the vocabulary of the classical languages. *Mundus* in Latin and *kosmos* in Greek meant a limited, organized system, bounded by the stars: the universe as a whole was called by Greek writers τὸ πᾶν, and by Latin writers (cursing their language for the absence of a definite article) *omne quod est, omne immensum*, and so on. This is a distinction without a

[2] "And so his splendid strength of soul prevailed/Outside he went, beyond the flaming ramparts of the world/And ranged the infinite whole in mind and thought's imagining." Trans. A. D. Winspear (New York, Harbor Press, 1952).

point in modern theory: *cosmo*logy is the study of the *universe*. But in this article I shall artificially reimpose the distinction in English, and use the word *world* for the limited *kosmos* or *mundus*, and reserve the word *universe* for the sum total of everything. The first point that I want to emphasize, because it is very often obscured or forgotten, is that no one in classical antiquity believed that the *world* is infinite. The controversy was not about the *existence* of a closed world, but about its status: is it all that there is, or is there something else too?

Before we try to pursue Epicurus and others beyond the *flammantia moenia mundi* (the flaming ramparts of the world), it may be as well to pause first, and reconsider these opening moves. Was there nobody in antiquity who denied that the earth is stationary, and that the stars move round it, and who might therefore have been in a position to abandon the notion of a sphere of stars at the boundary of the world? The answer is, of course, that there were a few imaginative spirits who floated the idea that the earth moves, but they made curiously little impact on the classical picture of the stars. There were some Pythagoreans who claimed that the centre of the world is occupied by fire—the finest element in the finest place—and the earth moves cozily around the fire.[3] There was Herakleides of Pontus, who argued that the earth rotates on its own axis once a day, and the stars are stationary.[4] And there was Aristarchus of Samos, who was apparently the first to put up the idea that the earth is in orbit round the sun.[5] In all of these theories, the apparent daily motion of the stars is merely an effect of the earth's motion.

It would appear, then, that they had no need to posit a *sphere* of stars. So long as the stars are thought to be in motion while still keeping the same relative positions, it is natural to think of them as a vast *corps de ballet*—creating a single harmony, as in pseudo-Aristotle *De mundo,* "as they sing and dance in concert round the sky" (399 a 12). But as soon as they are conceived to be stationary, there seems at first sight to be no cogent reason why they may not vary enormously in their distance from the earth. On this hypothesis, what reason is there to think of the stars that make up Orion's belt, for instance, as being located all at the same distance from us?

Well, there are reasons. First, there is the problem of parallax, which was known in antiquity. If the earth is moving in orbit round the sun, why do the stars not appear to change their relative positions as the earth moves from one extreme to the other of its orbit? Even if

[3] Cf. Walter Burkert, *Lore and Science in Ancient Pythagoreanism* (Cambridge, Mass., 1972), IV, 3 "The Cosmos of Philolaus."

[4] Fritz Wehrli, *Die Schule des Aristoteles VII: Herakleides Pontikos* (Basel/Stuttgart, 2nd ed., 1969), frr. 104-08. See H. B. Gottschalk, Heraclides of Pontus (Oxford, 1980), 58-87.

[5] Sir Thomas Heath, *Aristarchus of Samos: the Ancient Copernicus* (Oxford, 1913; rpt. 1959), 301-10.

the earth is stationary but rotating, the same problem arises for an observer on the earth's surface, because he is in an orbit around the center. There are two possible solutions. One is to retain the supposition that the stars are all equidistant from the center of the world. That reduces the parallax to a minimum, which can easily be thought of as undetectable by the naked eye. This is the solution that is attested for Aristarchus.[6] The second is to suppose that the stars do vary in their distance from us, but *all* of them are so far away from the earth that no parallax is observable. One may guess that the reason for rejecting this is that the stars do not appear to the observer to differ much in magnitude and brightness.[7]

There are also reasons that one might say come more from the heart than from the head, or more from poetry than from science. Even the most mechanistic of Greek philosophers of nature retained elements of a different, non-mechanistic model of the world—the model that gets its most powerful expression in Plato's *Timaeus*. The world is a ZOON, a living creature. But an animal needs a skin: the world's skin is its outer sphere. We find the analogy between the skin and the outer sphere of the cosmos drawn very explicitly in that strange and fascinating tract once thought to be by Hippocrates, *On Sevens*.[8] We find it in the words attributed to Leucippus and Democritus, who said that the world is enclosed in some kind of caul or membrane.[9] There is a tradition that Democritus was the first to call man a microcosm.[10] Lucretius substitutes the image of a walled city for that of the body, but that is not to be regarded as a very big shift, in view of the common association between the body and the social organization or body politic.[11]

There is just one hint in the direction of a quite different view that survives in the Doxographers, who say that according to Herakleides of Pontus every *star* is a world (*kosmos*) with its own earth and its own air.[12] This looks like a very promising theory, but unfortunately

[6] Archimedes, *Arenarius (Sand-Reckoner)* I, 4; translation in Morris R. Cohen and I. E. Drabkin, *A Source Book in Greek Science* (Cambridge, Mass., 1966), 108-09.

[7] Compare Kepler's arguments in *De stella nova serpentarii,* ch. 21 in his *Gesammelte Werke,* ed. Max Caspar (München: Beck, 1938), I, 253-54, quoted by Koyré, *op. cit.,* in n. 1, 62-70. Kepler argues that however far away from the earth we suppose the stars to be, we must still accept that the region around the earth and the sun is peculiarly empty of stars, and different in this respect from the rest of the universe.

[8] *De hebd.* ch. 6. The relevant part of this text is most conveniently found, with commentary, in M. L. West, "The Cosmology of [Hippocrates] *De hebdomadis*," *Classical Quarterly*, **21** (1971), 365-88.

[9] Diels-Kranz, *Vorsokratiker,*[5], 67 A 1 (32).

[10] *Ibid.,* 68 B 34.

[11] Lucretius, *De rerum natura*, I, 1102; II, 1144; III, 16; V, 371.

[12] Wehrli (*op. cit.,* in n. 4), fr. 113.

it is reported without any of its supporting context, and we are completely in the dark about its motivation. Herakleides is also credited with the statement that a man once fell to earth from the moon—the same origin that was assigned to the Nemean lion, and Helen.[13] Herakleides' star worlds may be equally lunatic. To be fair, it should be said that he wrote dialogues, and need not be thought of as subscribing to every view that is attributed to his pen.

We are justified, then, in leaving aside these eccentric viewpoints, and returning to the main theme: in classical times the antithesis to the Platonic-Aristotelian picture of the closed world was a view that itself accepted a kind of closed world, but asserted that this world is not the only thing that exists and not the only subject for philosophical inquiry. Some of the early Pre-socratics believed that outside the cosmos there is an unlimited supply of the stuff, whatever it was, from which the world grew.[14] The Stoics held that outside the cosmos there is an infinite extent of empty space. But the theory that has most significance is that outside the cosmos in which we live there is not only empty space but also matter, and moreover matter that forms itself into other worlds. This is the theory of Leucippus and Democritus, and Epicurus and Lucretius. It may perhaps have been held by earlier philosophers—that is a controversial point[15]; I propose to concentrate on the Atomists.[16]

The significance of this introduction to their theory is this. We have now seen that even for those who believed in the infinite universe, direct evidence—the evidence of our eyes—is confined to the bounded world. Beyond the fiery ramparts of the world nothing can be *seen*, everything must be guessed. That is one way of looking at it. But the obverse of that thought must be considered too. If there is a boundary set between the visible world and the rest of the universe outside, what can be the *use* of speculating about what goes on outside? We are stuck where we are: the phenomena are what we want to explain. What help shall we get from a theory of what goes on beyond

[13] *Ibid.*, fr. 115.

[14] See W. K. C. Guthrie, "The Presocratic World Picture," *Harvard Theological Review*, **45** (1952), 87-104.

[15] I agree that infinite worlds should not be attributed to Anaximander or Anaxagoras: arguments in G. S. Kirk, "Some Problems in Anaximander," *Classical Quarterly*, **5** (1955), 21-38, rpt. in *Studies in Presocratic Philosophy*, ed. D. J. Furley and R. E. Allen (London/New York, 1970), I, 335-40; Charles H. Kahn, *Anaximander and the Origins of Greek Cosmology* (New York, 1960), 46-53; Gregory Vlastos, "One World or Many in Anaxagoras?" (1959), rpt. in Furley and Allen, II, 354-60.

[16] Primary evidence for Democritus is collected in Salomo Luria, *Democritea* (Leningrad, 1970), frr. 343-66; for Epicurus, *Letter to Herodotus*, 73-74; Lucretius, *De rerum natura* II, 1023-1174.

the stars? For Epicurus, who said that the only point of doing physics was to set the mind free from anxiety, the question appears to be a pressing one.[17]

But before we look directly at the ancient Atomists' theory, I propose to digress for a minute or two to introduce a character from the seventeenth century, who may ultimately prove to be illuminating.

The main work of rebutting the closed world of Aristotelian theory was done by Copernicus, Kepler, Galileo, and Newton. At the time, there was a great revival of interest in the rival Greek theories that had been defeated by Plato and Aristotle. One of the leaders of this revival was the Provençal priest Pierre Gassendi: but I want to quote from his English follower Walter Charleton, son of the Rector of Shepton Mallet, and physician to Charles the First. Apart from making a great and early reputation for himself as a physician, Charleton published specialized studies on two curiously assorted topics: Epicureanism and Stonehenge.

I want to quote briefly from the book Charleton published in 1654: *Physiologia Epicuro-Gassendo-Charletoniana:* or *a Fabrick of Science Natural upon the Hypothesis of Atoms, founded by Epicurus, repaired by Petrus Gassendus, augmented by Walter Charleton.*[18]

Charleton adopted the hypothesis of atoms; but he rejected just that feature of Greek atomism that we are concerned with here. His second chapter has the title "That this world is the Universe" (my distinction between the world and the universe has excellent seventeenth-century English authority). He concedes that there is "an infinite Inanity or Ultramundane Space, yet can it *not* follow of necessity that there are Infinite Atoms contained in that Ultramundane Space, as Democritus and Epicurus preposterously infer: insomuch as it sounds much more concordant to reason, that there are no more Atoms, than those of which this single World was compacted."

Charleton offers some criticism of what he takes to be the Greek Atomists' argument for an infinite universe containing many worlds, and then produces his own reasons for rejecting the idea: first, that there is no mention of it in the book of Genesis, which he calls "Moses' inestimable diary or narrative of the Creation" and thus it is denied divine authority; and secondly, most of the ancient philosophers were against it, and so it lacks human authority.

[17] Epicurus, *Kyriai Doxai*, XI.

[18] There is a fine reprint by the Johnson Reprint Corporation (New York, 1966). Cf. M. Osler, "Descartes and Charleton," *JHI*, 40: 3 (July 1979), 445-56.

He ends the chapter with a fine rhetorical paragraph, which is worth repeating:

If any Curiosity be so immoderate, as to transgress the Limits of this All, break out of Trismegistus Circle, and adventure into the Imaginary Abyss of Nothing, vulgarly called the Extramundane Inanity; in the Infinity (or rather Indefinity) of which many long-winged Wits have, like seel'd Doves, flown to an absolute and total loss: the most promising Remedy we can prescribe for the reclaiming of such Wildness, is to advertise, that a serious Diversion of thought to the speculation of any the most obvious and sublunary natures will prove more advantageous to the acquisition of Science, than the most acute metaphysical Discourse, that can be hoped from the groveling and limited Reason of man, concerning that impervestigable Abstrusity; of which the more is said, the less is understood; and that the most inquisitive may find Difficulties more than enough within the little World of their own Nature, not only to exercize, but empuzle them. To which may be annexed that judicious Corrective of Pliny: "Furor est, profecto furor est egredi ex hoc mundo, et tanquam interna eius cuncta plane iam sint nota, ita scrutari extera." (p. 15) ["It is madness, downright madness, to step out of this world, and to study whatever lies outside as if everything inside it were already well known." *Natural History,* II 1, 4.]

Well, that gives point to our question: what was the motivation of this theory of a universe wholly beyond the reach of human senses? And if Charleton's Atomic Fabrick of Nature could do without the theory, why was it essential to the Greek Atomists?

The arguments of the earlier Greek Atomists, Leucippus and Democritus, as usual have to be retrieved from a largely hostile tradition. Aristotle mentions five arguments which, he says, are the plausible arguments in favor of the existence of an infinite.[19] The first is about the infinity of time, and the second about infinite divisibility; so these need not concern us now. Number three is that coming-to-be and passing away can be perpetual *only* if what comes-to-be is taken from an infinite source. Aristotle objects to this that it breaks down if coming-to-be and passing away are cyclical.[20] Since this is so obviously true, and was accepted by everyone who had been convinced by Parmenides that a thing that exists can never by annihilated, and the argument is not attributed to the Atomists, we can forget about it.

The fourth is this: that whatever is limited is always limited *against* something, and hence it follows that there *is* no ultimate limit, if one thing always has a limit against another. This is an argument with a venerable history going back at least as far as the Eleatic Melissus (that intellectual admiral who rather astonishingly defeated

[19] Aristotle, *Physics*, III, 4, 203 b 15-30.

[20] *Ibid.*, 8, 208 a 5-10.

Pericles' navy at Samos in 441 B.C.).[21] A version of it was included by Epicurus in his "elements of natural philosophy" in the *Letter to Herodotus*.[22]

The fifth, says Aristotle, is the principal argument, and the one that is most plausible. It is because there is no limit to the power of thinking of things that men attribute infinity to number, and to geometrical magnitude, and to the region outside the heavens. Archytas, the 4th-century Pythagorean, is credited with a picturesque version of this argument: "If I were at the edge of the world, as it might be in the region of the fixed stars, could I stretch out my hand or a stick into the outer region or not?"[23] Lucretius uses the same argument, substituting a javelin for the prosaic stick.[24] The point is, of course, that if you *can't* throw the javelin out of the finite world, there must be something outside to stop it. If you *can* throw it, there must be somewhere outside for it to go.

However, both of these arguments, the fourth and the fifth, in so far as they are persuasive, prove only that there is *something* outside the cosmos. It might be totally empty space (perhaps a space inhabited by nothing but a few experimental javelins and triumphantly waving hands). We have not yet been told anything about the motivation of the more significant theory of a space containing innumerable worlds.

Aristotle continues the fifth reported argument in favor of the existence of the infinite with something more meaty: "If what is outside the heavens is infinite, then it is thought that body is infinite too, and worlds. For why here, in the void, rather than there? Hence, if in one place, then in all places there should be bodily material."

"Why here, in the void, rather than there?" It is an excellent question, and an essential clue to the true meaning of the theory. For Plato and for Aristotle, there is no problem here. We have a cosmos, in their theory, and it is an organized whole with a determinate boundary and therefore a determinate center. The cosmos *has* no location: it *is* the location for everything else. There is no need to ask why it is here, rather than there.

But if anyone rejects Aristotle's arguments against the existence of void space, and accepts his opponents' arguments that there must be something outside the cosmos, then this question arises about the location of the cosmos as a whole. And it is a question with devastating impact in one respect above all: in the explanation of motion.

Aristotle based his theory of motion on the concept of the center of the universe. He offered no explanation, but simply stated as an

[21] Diels-Kranz, *Vorsokratiker*,[5] 30 B 6.
[22] *Letter to Herodotus*, 41.
[23] Simplicius, *In Physica*, 467.26 ff.
[24] Lucretius, I, 968-79.

observed fact that heavy objects naturally move *towards* the center of the universe, light objects move *away* from the center, and the material of the heavens moves *around* the center. This theory loses all plausibility when the center of the universe—the focus of all this movement—is believed to be nothing but a point in a void. If the void is infinite, then it is doubtful if it makes any sense to talk about a center at all. In any case, what can possibly be so special about one point in the void that makes *it* the focus of natural motion of the elements rather than any other place? "Why here, in the void, rather than there?" People asked awkward questions about the behavior of a piece of heavy matter in motion, when it reaches the center of the universe, supposing that it could. Would it stop dead in its tracks? or go on for a while and then turn back, like a pendulum? Since it is supposed to be travelling through a void, which offers no resistance to anything, what possible reason can be given for its not continuing in the same direction? The center cannot attract it, since it is just a point in the void, and the void has no attractive properties.

One way of solving this problem—the way taken by the Stoics, or some of them—was to suppose that all *matter* has a reciprocal attractive force. Since the void has no force whatever, and there is no counteracting force of repulsion, all the matter there is in the whole universe is naturally held together around a single center. There is nothing special about the location of this center in the void: it is simply the center of gravity, so to speak, of all the matter in the universe, wherever it happens to be. What prevents the whole system from collapsing upon itself to form an extremely dense ball of matter (like the black holes of contemporary theory) is the natural tension of matter—a fairly mysterious property that keeps every kind of matter in Stoic theory, at an approximately constant density.

So the Stoics were able to maintain the theory of a single, geocentric cosmos along with an infinite void. But this option was not available to the Atomists. It was not available because it would have meant attributing to matter a force of attraction which could not be reduced to collisions of atoms, whereas the only way in which atoms could interact, in Greek atomic theory, was by colliding with each other.

To the Atomists, then, it appeared that there was no answer to the question "why here, rather than there, in the void?" The most plausible account seemed to be that matter is more or less evenly distributed *throughout* the void.

Now we come at last to the crucial question. The Atomists recognized the force of the arguments that showed, first, that outside the boundary of the world there is infinite empty space, and, second, that in this space there is an unlimited supply of matter, of the same kind

as the matter of which our world is composed. The question is: what were they to suppose this matter does, what kind of motion were they to attribute to it?

Let us study this question for a moment from the epistemological point of view. It was a question about what lies beyond the phenomena. The phenomena we have to reckon with are the circular motions of the stars, the rectilinear motions of heavy and light bodies, together with the complexities of change of quality, and the growth, reproduction, and death of organic life. The Atomists reduced all of the latter to locomotions of atoms: they were left with what might appear to be an irreducible dualism— on the one hand, heavy bodies fall and light bodies rise in straight lines; on the other, the stars go round and round. The question they had to answer, then, was this: what is the relation between this observed dualism of circular and rectilinear motion, and the *un*observed motion of the atoms in the "Extramundane Inanity?"

It is worth pausing briefly to reflect on the magnitude of this question of the two kinds of motion, and the way other philosophers handled it. For both Plato and Aristotle, this duality was of immense significance. Both made the contrast between circular and rectilinear motion a symbol of the contrast between the eternal and the transient, hence also between the psychical and the physical, even the divine and the mortal. By so doing, they were not necessarily taking the problem of the stars out of the realm of science altogether—one can be scientific about the soul and the gods, and to a degree they were—but they were at least setting up a *different* science of the stars, one in which the criteria for the acceptance of a conclusion were not the same as those in the science of perishable nature. The uniqueness of the cosmos, in their view, made it easier to do this. They did not have to work out the kind of explanation that would present our cosmos as an instance of a general law.

There is an argument of the Atomists that is relevant here.[25] It is an inductive argument. If we look around at the objects in the world of which we can get a clear view, we never find an instance that is the only one of its kind. Hence we should accept it as a universal truth that there is nothing unique. So if anything appears to be unique among the things that we cannot examine closely—for example, the sun, the moon, the earth—we should conclude that the appearance is misleading, and that there are other instances somewhere out of our view.

It is a consequence of this that our cosmos must be seen not as any kind of special case, but as a specimen of a kind. Any explanation of what goes on in the cosmos has to be capable of being generalized—

[25] Lucretius, II, 1077.

given the same conditions elsewhere, the same results must be expected to follow.

How, then, are these considerations to be applied to the *dual* motions that are observed in the cosmos? It seems to be the circular motion that presents the main problem. A circle needs a center, and there is no center in the infinite void; so it is impossible to suppose, as Aristotle did, that there is a kind of matter which naturally moves in a circular orbit around a center. The only possible conclusion was that the circular motion is a secondary, derivative motion: it depends on the formation of something with a center.

In principle, it seems to me that there were just two options open to the Atomists when they faced the problem of inferring a theory of extramundane motion from the observed motion of matter inside the cosmos. Either they could accept rectilinear motion as basic, and try to show how circular motion could develop from it; or they could hold that there is *no* basic form of motion at all, and try to show how both circular motion and rectilinear motion due to weight might develop from the random wanderings or jostlings of atoms.

In principle, two options: but it seems perhaps too convenient and suspiciously neat that according to present day orthodoxy Democritus chose the latter and Epicurus the former.

The evidence concerning Epicurus is much more direct and unambiguous, so we will take him first, out of chronological order.[26] In his theory, the basic motion is what we observe on earth as a rectilinear downward movement of free falling heavy bodies. Upward motion, of fiery things (also basic and natural in Aristotle's system), was explained as being due to the pressure of more massive bodies crowding together—like a lemon pip squeezed between the fingers. the circular motion of the heavenly bodies is explained by analogy with various homely and familiar devices in which we see rectilinear motion translated into circular motion—basically, water wheels.[27] The stars are part of a unified compound with earth at its center, and the earth forms the hub of the star wheels, which are blown or washed round by streams of atoms falling past in straight lines.

Now, viewed from some scientific points of view, this theory has all the marks of a disaster. In the first place, since there is no center in the infinite void, no focal point at all, downward motion, which is

[26] The most connected ancient account of the Epicurean theory is in Lucretius, *De rerum natura*, II, 62-332.

[27] Lucretius, V, 509-33, 614-782. See J. G. Landels, *Engineering in the Ancient World* (London, 1978), 16-27. Although water wheels were familiar, there is no evidence for rotary windmills in classical antiquity. Lucretius imagines winds blowing the stars around, but quotes the analogy of water wheels (516).

basic, cannot be defined as in Aristotle's theory or the Stoic theory by its end point at the center. It can be defined with the help of the axiom of parallels, but only if *some* line is taken as given. The Epicureans chose as the datum the line of free fall—that is to say, the line on which they observed things to fall, in the Garden at Athens—and asserted that everything that falls freely, anywhere in the infinite universe, falls parallel to this line. The disaster is, of course, that in fact Aristotle was right: a stone dropped at Athens does not fall parallel to a stone dropped at Stagira; they both fall towards the center of the earth. The Epicurean theory demands that all downward fall be parallel: that means that it works only if the earth is flat, since so far as can be observed, the line of fall is everywhere perpendicular to the earth's surface.

The second disaster was this: the chosen model (of water wheels and sail boats) offered no good explanation of the outstanding feature of star motion: its absolute regularity. Greek astronomy, with the help of the Near East, had already reached an advanced level of accuracy in predicting the positions of the stars, planets, sun, and moon; they had already worked out sophisticated mathematical models for computing these positions. Now the Epicureans offered a theory that the heavens move because they are blown around—and the wind notoriously bloweth where it listeth, and never on schedule. The implausibility is compounded by the Epicurean habit of suggesting alternatives on matters that cannot be decided by direct inspection: perhaps it is a wind that blows outside, perhaps inside, perhaps it is more like a water wheel. This kind of thing earned (and earns) contempt from astronomers.

The situation illustrates a recurrent dilemma in ancient natural philosophy. Here we have a *physical* theory of the motion of stars that has the merits of needing no mythological props, and using nothing but familiar models drawn from the natural world—but it is a theory that is a mathematical disaster. On the other hand, we have a beautiful mathematical model, the model of concentric spheres, later patched up with epicycles, that is physically preposterous. The ancient world never succeeded in putting both models together.

Finally, back to Democritus, and to a problem which still seems extremely puzzling.

Practically no direct evidence survives. We hear from Aristotle that Democritus did not say what is the natural motion of bodies, but only that they move because of collisions.[28] That seems to mean that Democritus cannot have held the Epicurean theory of downward fall. We also hear that Democritus did not admit an *origin* of motion as a

[28] Aristotle, *De caelo*, III, 2, 300 b 8.

whole.[29] So it seems—this is the usual view nowadays—that according to Democritus the basic motion of atoms in the infinite void is a random jostling in which no factor but collision plays a part.

What interests us now is how Democritus derived from this formless jostling, if that is the correct picture, the two motions observable in our cosmos. We have some information about his derivation of circular motion. Instead of the water-wheel, Democritus chose the vortex or whirlwind or whirlpool—the DINE who Aristophanes said had usurped the kingdom of Zeus.[30] In certain conditions, we can observe water and wind spontaneously forming circular whirls, the most spectacular examples being the tornadoes and minor "twisters" of the American mid-West, and similar phenomena in the Mediterranean world. We have to believe according to Democritus that star motions are the relic of such a whirl. One of the observed effects is that massive objects congregate at the center of the whirl, where they are relatively exempt from the circular motion and come to a halt, while less sluggish objects fly out to the exterior and continue to whirl around. This is the model for the formation of the stationary, disc shaped earth, with the heavenly bodies in circular orbits around it.

But does this model also explain why a stone dropped from a height falls of its own accord in a line perpendicular to this flat earth? Epicurus had no need to work out an explanation of this: it was the datum from which other motions were derived. But if Democritus did not follow that path, how *did* he explain the second one of the two motions in the cosmos?

Some of the standard modern books say that downward fall is one aspect of the tendency of heavy bodies to seek the center of the whirl.[31] But that will not do. What needs to be explained is a linear motion at an angle to the central axis of the whirl, not from the circumference *to* the central axis.[32] It is true that some rectilinear up and down motions are produced by whirls: everyone has seen bits of paper rise vertically in a whirlwind, and notoriously boats get sucked down by whirlpools. But was that really the model that Democritus

[29] Aristotle, *Physics*, VIII, 1, 250 b 18-21 (no names, but the attribution to the Atomists, confirmed by Simplicius, seems certain).

[30] Diels-Kranz, *Vorsokratiker*,[5] 68 B 167. Aristophanes, *Clouds*, 380. See John Ferguson, "DINOS," *Phronesis*, **16** (1971), 97-115; Steven S. Tigner, "Empedocles' Twirled Ladle and the Vortex-Supported Earth," *Isis*, **65** (1974), 433-47.

[31] For example, W. K. C. Guthrie, *A History of Greek Philosophy*, II (Cambridge, England, 1965), 410.

[32] Greek cosmologists who used the hypothesis of a vortex to explain the origin of the cosmos had to face the problem that the axis of the whirling stars is visibly not perpendicular to the horizon (in Greece). They commonly explained this by the *ad hoc* assumption that the heavens tilted somehow, after the formation of the earth. Democritus' version of this is reported by Aetius, II, 12, 2 (*Vorsokratiker*,[5] 68 A 96).

suggested to explain downward fall? Even if we concede that the initial whirl of atoms, at the time of the formation of the cosmos, might plausibly explain some features of the upward and downward distribution of matter in the cosmos, is there any plausibility in suggesting that the remainder of that original whirl, now confined to the outer shell of the cosmos, explains why a stone falls to earth here at the center? If Democritus dropped a heavy pot to the floor of his house in Abdera, what could he say? He could not say, like Aristotle, that it is seeking the center of the universe, as all heavy objects do; he could not say, like the Stoics, that it is attracted to the center of all the material body in existence; he could not say, according to the orthodox account of his theory, like Epicurus, that this is just what every material body in the universe does if not prevented; could he really say, instead, that it fell down like that *because* the stars and the sun and moon out there are going round and round in a whirl? It seems very implausible.

Elsewhere I have offered some arguments for thinking that Democritus' view was after all similar to that of Epicurus, and included the idea of a natural downward motion of atoms, at right angles to the earth's flat surface.[33] But this is a very controversial position, which entails accusing Aristotle, our best source of information, of ignorance or of extremely ambiguous writing. For the present, this problem must be left undecided.

It can be asserted with confidence, however, that the problem of motion is what motivated the Atomists' theory of the infinite universe. Although it is not mentioned explicitly either in Aristotle's discussion of Democritus, or in Epicurus' *Letter to Herodotus*, it comes through clearly enough in Lucretius, especially in Book 5. And we can confirm it by reflecting on this question: what else in their philosophy of nature would the Atomists have had to give up, if they had abandoned the theory of an infinite universe containing plural worlds? I see no way in which they could have explained the dual motions of the cosmos without abandoning some vital first principle of their system. They would have had to abandon their simple theory of matter, and divide it into two different kinds, and in addition they would have had to attribute forces of attraction and repulsion to it, acting at a distance through the void or acting through some invisible, non-resistant material like the ether of early modern physics; or else they would have had to take an Aristotelian stance and treat the two motions as irreducible data of the universe; or else they would have had to re-import gods.

[33] "Aristotle and the Atomists on Motion in a Void," in Peter K. Machamer and Robert G. Turnbull, eds.; *Motion and Time, Space and Matter* (Columbus, Ohio, 1976), 83-100. [See now D. O'Brien, *Theories of Weight in the Ancient World,* vol. I: *Democritus on Weight and Size* (Paris and Leyden, 1981).]

It was this last option that enabled the seventeenth-century atomist Walter Charleton to do without the postulate of plural worlds. In his view, God had created just that amount of matter needed for our world, and had endowed it with just those capacities for motion which enabled it to perform as it does. In a similar vein, Richard Bentley, in his *Confutation of Atheism*, argued at length against the Epicurean theory of the origin of our world in the infinite universe, because he saw it as a rival to the creation story.[34] The Epicurean theory was that given an infinite universe and infinite time, the matter in the universe, in random motion, must eventually produce everything that can be produced out of matter[35]—the argument later familiar with type-writing monkeys in the leading role. Bentley will not accept it: "Let us suppose two ships, fitted with durable timber and rigging, but without pilot or mariners, to be placed in the vast Atlantic or the Pacific Ocean, as far asunder as may be; how many thousand years might expire before those solitary vessels should happen to strike one against the other?" By a calculation of his own, Bentley worked out that atoms are comparatively *further* apart from each other, and hence even less likely to collide. Hence, the infinite universe cannot give birth to the finite, organized cosmos without divine intervention.

Whatever may be thought of the plausibility of these two positions, there is at least this much to be said for the theory of the ancient Atomists—and it is something of great importance. They made the first bold effort to construct a unified theory of motion. They dispensed with the cosmic Mind of Anaxagoras, the forces of Love and Strife in Empedocles, the demiurge of Plato's *Timaeus* and the world soul of the *Laws*. They had no need to postulate Aristotle's heavenly spheres, reeling with love for their divine Unmoved Mover, nor to add a fifth element endowed with natural spin. If unity and simplicity are virtues in an explanatory hypothesis, then those virtues can be set in the balance against the naiveté of some of the theory's detail.

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[34] Richard Bentley, *Works*, ed. Alexander Dyce (London, 1836-38), III, 158-62.
[35] Lucretius, IV, 416-31.