Astronomy and Cosmology

INTRODUCTION

ASTRONOMY could take its place in this catalog of ideas on the ground that several of the great books are monuments of astronomical science, exemplifying the imaginative and analytic powers which have made it one of the most remarkable triumphs of the human mind. Its claim might further be supported by the fact that other great books—of mathematics, physics, theology, and poetry—have a context of astronomical imagery and theory. But the inclusion of astronomy can be justified by what is perhaps an even more significant fact, namely, that astronomical speculation raises problems and suggests conclusions which have critical relevance for the whole range of the great ideas.

Man has used astronomy to measure, not only the passage of time or the course of a voyage, but also his position in the world, his power of knowing, his relation to God. When man first turns from himself and his immediate earthly surroundings to the larger universe of which he is a part, the object which presses on his vision is the overhanging firmament with its luminous bodies, moving with great basic regularity and, upon closer observation, with certain perplexing irregularities. Always abiding and always changing, the firmament, which provides man with the visible boundary of his universe, also becomes for him a basic, in fact an inescapable, object of contemplation.

Careful and precise astronomical observations antedate the birth of astronomy as a science. The early interest in the heavenly bodies and their motions is often attributed to the usefulness of the predictions which can be made from a knowledge of celestial phenomena.

Whether their motive was entirely utilitarian, or partly religious and speculative, the Egyptians and Babylonians, we learn from Herodotus, undertook patient study of the heavens. They observed and recorded with immense persistence. They calculated and predicted. They turned their predictions to use through the priestly *office* of prophecy to foretell eclipses, tides, and floods, and they employed their calculations in the mundane arts of navigation and surveying to guide travel and fix boundaries. But they did not, like the Greeks, develop elaborate theories which sought to organize all the observed facts systematically.

With the Greeks, the down-to-earth, everyday utility of astronomy seems to count for less than its speculative grandeur. The dignity which they confer upon astronomy among the disciplines reflects the scope and majesty of its subject matter. The Greek astronomer, concerned as he is with figuring motions that range through the whole of space and are as old as time or as interminable, takes for his object the structure of the cosmos.

Aristotle and Plato pay eloquent tribute to the special worth of astronomy. In the opening chapter of his *Metaphysics,* Aristotle associates astronomical inquiry with the birth of philosophy. "Apart from usefulness," he says, "men delight... in the sense of sight" and, he adds, "it is owing to their wonder that men both now begin and at first began to philosophise." They wondered first about "the obvious difficulties," but little by little they advanced to "greater matters," and "stated difficulties ... about the phenomena of the moon and sun and stars, and about the genesis of the universe." In his own philosophical thought, Aristotle's treatise *On the Heavens* is not only one of the basic natural sciences but certain of its principles have general significance for all the other parts of his physical science.

A wider view of the importance of astronomy is taken by Plato. In the *Timaeus,* he dwells on "the higher use and purpose for which God has given eyes to us... Had we never seen the stars, and the sun, and the heaven," Timaeus says, "none of the words which we have spoken about the universe would ever have been uttered ... God invented and gave us sight," he continues, "to the end that we might behold the courses of intelligence in the heaven, and apply them to the courses of our own intelligence which are akin to them, the unperturbed to the perturbed; and that we, learning them and partaking of the natural truth of reason, might imitate the absolutely unerring courses of God and regulate our own vagaries."

For Plato, then, man's intellectual relation to the heavens does more than initiate philosophy. Man's self-rule, his purity and peace of soul, is at stake in that relation. That is one reason why, in both *The Republic* and the *Laws,* Plato makes astronomy a required part of the curriculum for the education of rulers. "He who has not contemplated the mind of nature which is said to exist in the stars ... and seen the connection of music with these things, and harmonized them all with laws and institutions, is not able," the Athenian Stranger says in the *Laws,* "to give a reason for such things as have a reason."

Plato considers the opposition to astronomy on religious grounds by those who think that men who approach celestial phenomena by the methods of astronomy "may become godless because they see ... things happening by necessity, and not by an intelligent will accomplishing good." His answer points out that one of the "two things which lead men to believe in the gods ... is the argument from the order of the motion of the stars and of all things under the dominion of the mind which ordered the universe." It was a false understanding of these matters which "gave rise to much atheism and perplexity."

THE ISSUES RAISED by Plato concerning the importance of astronomy for purification and piety, for education and politics, run through the tradition of western thought. Though they are somewhat transformed in the context of Jewish and Christian beliefs, and altered by later developments in the science of astronomy itself, they remain as matters on which an author's strong assent or dissent forcefully reflects his whole intellectual position.

On the one hand, astronomers like Ptolemy, Copernicus, and Kepler, for all their differences on points of scientific theory, seem to concur in reaffirming Plato's conception of the bearing of their science on religion and morals. Lucretius and Augustine, on the other hand, while not agreeing with each other, seem to disagree with Plato. In the tradition of western thought, they represent different types of opposition to the Platonic view.

Where Plato and his followers, including religious Christians like Copernicus and Kepler, hold that true piety profits from astronomical study, Lucretius hopes that astronomy may help to free men from religious superstitions. If when "contemplating that great world/Of heavenly space ... And pondering the ways of sun and moon," they do so "with a peaceful mind" because they see only the workings of natural law and no evidences of a controlling power in the will of the gods, then men achieve the natural piety of the scientist—different in the opinion of Lucretius from the false worship which is based on fear.

From his own experiences in dealing with the astronomy of the Manichaean sect in relation to their religious doctrine, Augustine insists that the teachings of religion in no way depend upon astronomy. He denies that such knowledge is in any way essential to true piety. "It would be foolish to doubt," he writes, that "a man, though he may not know the track of the Great Bear, is altogether better than another who measures the sky and counts the stars and weighs the elements, but neglects you who allot to all things their size, their number, and their weight."

When Manes, a Manichaean scholar, "was shown to be wrong in what he said about the sky and the stars and the movements of the sun and moon ... although these matters are no part of religious doctrine," his religious teachings, according to Augustine, inevitably suffered ridicule because of his pretension that they derived support from a science of the heavenly bodies. Augustine would disengage theology from astronomy. His position anticipates that later taken by Cardinal Barberini who, during the controversy over the Copernican hypothesis, is reported to have told Galileo that astronomy and religion have quite separate tasks, the one teaching how the heavens go, the other how to go to heaven.

Still another point of view on the importance of astronomy is represented in the skeptical and humanist attitude of Montaigne. "I feel grateful to the Milesian wench" who advised the philosopher Thales "to look rather to himself than to the sky." In saying this, or in quoting with approval the question asked of Pythagoras by Anaximenes—"W hat sense have I if I can amuse myself with the secret of the stars, having death or slavery ever present before my eyes?"—Montaigne intends more than a preference for the moral over the natural sciences. He regards astronomical inquiry as a prime example of man's "natural and original malady"—presumption. It is presumptuous to suppose that our minds can grasp and plot the course of the heavens when we fail to comprehend things much nearer at hand. Hence Montaigne advises everyone to say, in the spirit of Anaximenes: "When I am battered by ambition, avarice, temerity, and superstition, and have other such enemies of life within me, shall I go dreaming about the revolutions of the earth?"

Kant can be as critical as Montaigne of the frailty of human knowledge. "The investigations and calculations of the astronomers," he writes, have shown us "the abyss of our ignorance in relation to the universe." But Kant—an astronomer himself as well as a moralist—does not, therefore, advise us to forsake the study of the heavens. On the contrary, he recommends it not only for its scientific value, but for its moral significance.

"Two things," Kant declares in a passage which has become famous, "fill the mind with ever new and increasing admiration and awe, the oftener and more steadily we reflect on them: the starry heavens above and the moral law within." The two fit together to produce a single effect. Astronomy with its view "of a countless multitude of worlds annihilates, as it were, my importance as an *animal* creature." Morality "elevates my worth as an *intelligence* by my personality, in which the moral law reveals to me a life independent of animality and even of the whole sensible world."

Kant's association of the starry heavens with the moral life is not so much an echo of, as a variant upon, Plato's precept that we apply "the courses of intelligence in heaven... to the courses of our own intelligence." But in one passage of Freud we find an almost complete return to the Platonic insight. "Order has been imitated from nature," he writes; "man's observations of the great astronomical periodicities not only furnished him with a model, but formed the ground plan of his first attempts to introduce order into his own life."

ASTRONOMY HAS connections with biology and psychology, as well as with mathematics and physics. The obvious fact that the sun supports terrestrial life—operating here as a unique and indispensable cause—occasions the inference by Aquinas that it may also operate as a cause in the production of new species by spontaneous generation from putrefying matter. This notion bears some resemblance to the theory in contemporary genetics of the effect of cosmic radiations upon gene mutations.

Unlike these notions in biology, speculations concerning celestial influences upon psychological phenomena seem to cross the line between astronomy and astrology. Sometimes the influence upon man and his actions is found in the constellations attending a nativity; sometimes it is a particular influence of the sort still signified by the meaning of the word "lunacy"; and sometimes omens and auguries are read in the aspect of the heavens.

The chapters on PROPHECY and SIGN AND SYMBOL deal with the issues raised by astrology. Problems more closely associated with astronomical science and speculation are treated in other chapters. The cosmological problem of the origin of the material universe is discussed in the chapters on ETERNITY, TIME, and WORLD; the question of its size in the chapter on SPACE; the question of whether the celestial spheres are themselves alive or are moved by intelligences or spirits in the chapters on ANGEL and SOUL; and the question of the nature of the heavenly bodies in the chapter on MATTER.

This last problem is of crucial significance in the history of astronomy itself. Opposed theories of the motions of the heavenly bodies become correlated with opposed theories concerning their matter—whether that is different in kind from terrestrial matter or the same. It is with reference to these related issues that what has come to be called "the Copemican revolution" represents one of the great crises, certainly one of the most dramatic turning points, in the development of astronomy, and of physics and natural science generally.

The Copemican revolution did not take place by the improvement and enlargement of astronomical observations alone, nor even by the effect of these on alternative mathematical formulations. If it had not been accompanied by the radical shift from ancient to modern physics—especially with regard to the diversity or uniformity of the world's matter—the Copemican hypothesis concerning the celestial motions would have been no more than a mathematical alternative to the Ptolemaic hypothesis. Copernicus seems to advance it only as such, but in the hands of Kepler, Galileo, and Newton it becomes much more than that. They, rather than Copernicus, seem to accomplish the revolution connected with his name.

When their contribution is neglected or inadequately grasped, the Copemican revolution appears to be, as is often popularly supposed, merely a shift in astronomical theory. The problem being to organize mathematically the *apparent* motions of the heavens, Copernicus offers an alternative solution to that of Ptolemy. Instead of treating the earth as stationary and central in the cosmic system, Copernicus attributes three motions to the earth by treating it as a planet which revolves around the sun, spins on its axis,_and varies the inclination of its axis with reference to the sun.

What is usually supposed to be revolutionary about this hypothesis is its effect on man's estimate of himself and his place or rank in the universe. On either of the rival hypotheses, the apparent motions of the heavens remain unaltered, but not man's conception of himself, of his earth, or of the universe in which the earth's orbit cuts so small a figure. As Kant suggests, man's stature seems to shrink. He becomes "a mere speck in the universe" which has been enlarged to infinity, or at least to an unimaginable immensity. He is displaced from its center to become a wanderer with his planet. Humanity's self-esteem, according to Freud, was thus for the first time deeply wounded; he refers to the theory that "is associated in our minds with the name of Copernicus" as the "first great outrage" which humanity "had to endure from the hands of science."

It has been questioned whether this interpretation of the Copemican revolution fits all the documents in the case. Freud may be accurately reporting a popular feeling which, since the 18th century, has become a widespread consequence of Copemican and post-Copernican astronomy. But in earlier centuries when the Ptolemaic system prevailed, or even after Copernicus, the appraisal of man's rank seems to depend more upon the position he occupies in the hierarchy of God's creatures—below the angels and above the.brutes—than upon the place or motion of the earth, or the size of the world.

Boethius, for example, finds the Ptolemaic universe large enough to remind man of the infinitesimal space he occupies. Dante, too, comments on the smallness of the earth in the scheme of things. When in his visionary travel Dante reaches the Empyrean, he looks down upon the earth and "with my sight," he tells us, "I returned through all and each of the seven spheres, and saw this globe such that I smiled at its paltry semblance; and that counsel I approve as best which holds it for least."

Kepler, a passionate Copemican deeply concerned with the human significance of astronomy, can be found arguing that the new hypothesis involves something more fitting for man than the old. In his last argument in defense of the Copemican view against that of

Tycho Brahe as well as that of Ptolemy, he declares, "it was not fitting that man, who was going to be the dweller in this world and its contemplator, should reside in one place as in a closed cubicle ... It was his office to move around in this very spacious edifice by means of the transportation of the Earth his home." In order properly to view and measure the parts of his world, the astronomer "needed to have the Earth a ship and its annual voyage around the sun."

Yet the very fact that Kepler argues in this manner may be interpreted as indicating his sense of the drastic implications for man of the altered structure of the universe. Kepler may even be thought to announce the problem of the so-called "Copernican revolution" when, in denying that the earth can any longer "be reckoned among the primary parts of the great world," since it is only a part of a part, *i.e.,* the planetary region, he deliberately adds the qualification: "But I am speaking now of the Earth in so far as it is a part of the edifice of the world, and not of the dignity of the governing creatures which inhabit it."

Whether or not it was the traumatic blow to the human ego which Freud conjectures, there can be little doubt that the shift from Ptolemy to Copernicus involved a real shock to the imagination. The Ptolemaic system conforms to the look of the world, which is indeed the reason why it is still the one used in practical courses in navigation. Here again Kepler defends Copernicus by explaining why "our uncultivated eyesight" cannot be other than deceived and why it "should learn from reason" to understand that things are really different from the way they appear.

A certain disillusionment may result from this affirmation—repeated by every schoolboy who is taught the Copernican system—that, despite what we see, the sun does not move around the earth, and the earth both rotates and revolves. It undermines the trust men placed in their senses and the belief that science would describe the world as they saw it. In order to "save the appearances," that is, to account for the phenomena, science might henceforward be expected to destroy any naive acceptance of them as the reality.

Furthermore, though the Ptolemaic world was very large, the Copernican universe was much larger. Whereas in the former the radius of the earth was deemed negligible in relation to the radius of the sphere of the fixed stars, in the new universe the radius of the earth's orbit around the sun was negligible in relation to the same radius of the sphere of the fixed stars. It can hardly be doubted that this intensified some men's sense of almost being lost in an abyss of infinity. "I see those frightful spaces of the universe which surround me," Pascal writes, "and I find myself tied to one corner of this vast expanse, without knowing why I am put in this place rather than in another." When he regards the world's immensity as "the greatest sensible mark of the almighty power of God," Pascal experiences an awe which for him is qualified by reverence. Other men may experience the same feeling, but less with reverence than with a gnawing loneliness, born of the doubt that so vast a cosmos—if cosmos it is rather than chaos—can have been beneficently designed as man's habitation.

WHATEVER THE TRUTH about the effect of the Copernican theory in the order of opinion, imagination, and feeling, it did produce a direct result on the intellectual plane. It, more than any other single factor, led to the overthrow of certain crucial doctrines which had been linked together in the physics and astronomy of Aristotle; it thus radically changed the fundamental principles in terms of which man had understood the order and unity of nature. That scientific event deserves not only the name but the fame of the "Copernican revolution."

The revolution in the realm of theory goes much deeper than the substitution of one mathematical construction for another to describe the motions of the world's great bodies. As Freud points out, the heliocentric hypothesis associated with the name of Copernicus was known to the Alexandrian astronomers of antiquity. It is, for example, attributed to Aristarchus of Samos by Archimedes in *The Sand-Reckoner.*

As far as the earth's rotation is concerned, Ptolemy admits it is quite "plausible" to suppose "the heavens immobile and the earth turning on the same axis from west to east very nearly one revolution a day... As far as the appearances of the stars are concerned," he goes on, "nothing would perhaps keep things from being in accordance with this simpler conjecture."

Why, then, does Ptolemy reject a supposition which is not only plausible but also, in accounting for the appearances, *simpler?* In part the answer may be that he does so because the contrary supposition conforms to our ordinary sense-experience of the earth's immobility and the motions of the heavens from east to west. But that is far from being the most important part of the answer. Ptolemy indicates the crucial part when he tells us that the otherwise plausible supposition of a rotating earth becomes "altogether absurd" when we consider the speed and direction of the motions of bodies within the earth's own atmosphere. His strongest count against the supposition is that it does not conform to the Aristotelian physics which distinguishes between natural and violent motions, assigns certain fixed directions to the natural motions of each of the four elements of matter, and denies that these elementary kinds of terrestrial matter enter into the composition of the heavenly bodies.

That Aristotle's physics and cosmology lie at the very heart of the issue is confirmed by the way in which Kepler later argues for the Copernican theory against Ptolemy. He does not defend its truth on the ground that it accounts for observable facts which the Ptolemaic hypothesis cannot handle. Nor does he prefer it merely because it is mathematically the simpler hypothesis. On the contrary, he specifically notes that anything which can be claimed on mathematical grounds for Copernicus over Ptolemy can be equally claimed for Brahe over Ptolemy. (Brahe's theory was that while the other planets revolve around the sun, the sun, with its planets, revolves around a stationary earth.) According to Kepler, the truth of these competing theories must finally be judged *physically,* not *mathematically,* and when the question is put that way, as it is not by Copernicus himself, Copernicans like Kepler, Galileo, and Newton take issue with what had been associated with the Ptolemaic theory—the physics of Aristotle.

IN ORDER TO EXAMINE this issue, it is necessary to state briefly here certain features of Aristotle's physics which are more fully discussed in the chapters on CHANGE, ELEMENT, MECHANICS, and PHYSICS.

Just as Ptolemy's astronomy conforms to what we see as we look at the heavens, so Aristotle's physics represents a too simple conformity with everyday sense-experience. We observe fire rising and stones falling. M ix earth, air, and water in a closed container, and air bubbles will rise to the top, while the particles of earth will sink to the bottom. To cover a multitude of similar observations, Aristotle develops the theory of the natural motions and places of the four terrestrial elements—earth, air, fire, and water. Since bodies move naturally only to attain their proper places, the great body which is the earth, already at the bottom of all things, need not move at all. Being in its proper place, it is by nature stationary.

Two other observations exercise a decisive influence on Aristotle's theory. The naked eye sees no type of change in the heavenly bodies *other than* local motion or change of place. Unlike terrestrial bodies, they do not appear to come into being or perish; they do not change in size or quality. Furthermore, whereas the natural local motion of sublunary bodies appears to approximate the path of a straight line, the local motion of the celestial bodies appears to be circular rather than rectilinear.

To cover these observations, Aristotle's theory posits a different kind of matter for celestial and terrestrial bodies. An incorruptible matter must constitute the great orbs which are subject to local motion alone and have the most perfect kind of local motion—that of a circle. Since they are subject to generation and corruption, to change of quality and quantity, and are in local motion along straight lines, terrestrial bodies are of a corruptible matter.

The interconnection of all these points is marked by Aquinas when he summarizes Aristotle's doctrine. "Plato and all who preceded Aristotle," he writes, "held that all bodies are of the nature of the four elements" and consequently "that the matter of all bodies is the same. But the fact of the incorruptibility of some bodies was ascribed by Plato, not to the condition of matter, but to the will of the artificer, God ... This theory," Aquinas continues, "Aristotle disproves by the natural movements of bodies. For since he says that the heavenly bodies have a natural movement, different from that of the elements, it follows that they have a different nature from them. For movement in a circle, which is proper to the heavenly bodies, is not by contraries, whereas the movements of the elements are mutually opposite, one tending upwards, another downwards ... And as generation and corruption are from contraries, it follows that, whereas the elements are corruptible, the heavenly bodies are incorruptible."

The same points which Aquinas relates in his defense of the Aristotelian theory, Kepler also puts together when he expounds that theory in order to attack it and the Ptolemaic astronomy which tries to conform to it. "By what arguments did the ancients establish their opinion which is the opposite of yours?" he asks. "By four arguments in especial: (i) From the nature of moveable bodies. (2) From the nature of the motor virtue. (3) From the nature of the place in which the movement occurs. (4) From the perfection of the circle." He then states each of these arguments and answers each in turn.

WHAT IS EXTRAORDINARY about Kepler's attack upon the Ptolemaic astronomy cannot be understood without examining Ptolemy's defense of his theory, a defense which Copernicus meets in Ptolemy's own terms rather than, as Kepler does, by going outside them.

Though his expressed intention was to construct a mathematical theory of the celestial motions which would also conform to Aristotle's physics, Ptolemy, when he finished, recognized that the complications he had been compelled to add in order "to save the appearances" left him with a theory that did not conform to Aristotle's doctrine of the perfect circular motion of the heavenly spheres. Instead of abandoning Aristotle's physics, he defended his theory on the ground that astronomy, being mathematical rather than physical, could admit such "unrealistic" complications if they served the purposes of calculation and of "saving the appearances."

In the thirteenth and last book of *The Almagest,* when he faces the fact that his mathematical devices have become exceedingly difficult—and strained from the point of view of the Aristotelian reality—Ptolemy writes: "Let no one, seeing the difficulty of our devices, find troublesome such hypotheses ... It is proper to try and fit as far as possible the simpler hypotheses to the movements of the heavens; and if this does not succeed, then any hypotheses possible. Once all the appearances are saved by the consequences of the hypotheses, why should it seem strange that such complications can come about in the movements of heavenly things?" We ought not to judge the simplicity of heavenly things by comparison with what seems to be simple in the explanation of earthly phenomena. "We should instead judge their simplicity from the unchangeableness of the natures in the heavens and their movements. For thus they would all appear simple, more than those things which seem so here with us."

Ignoring the supposition that simplicity must be judged differently in different spheres, Copernicus challenges Ptolemy on his own grounds when he proposes "simpler hypotheses" to fit "the movements of the heavens." But in doing so, he seems to adopt the traditional view of the mathematical character of astronomical hypotheses. Yet, as will appear, he does not adopt this view in the unqualified form in which Andreas Osiander states it in his preface to *On the Revolutions of the Heavenly Spheres.*

"It is the job of the astronomer," Osiander writes, "to use painstaking and skilled observation in gathering together the history of the celestial movements, and then—since he cannot by any line of reasoning reach the true causes of these movements—to think or construct whatever causes or hypotheses he pleases, such that, by the assumption of these causes, these same movements can be calculated from the principles of geometry, for the past and for the future too.

"It is not necessary," he adds, "that these hypotheses should be true, or even probable; it is enough if they provide a calculus which fits the observations. When for one and the same movement varying hypotheses are proposed, as eccentricity or epicycle for the movement of the sun, the astronomer much prefers to take the one which is easiest to grasp."

What distinguishes Kepler from both Ptolemy and Osiander is the way in which he is concerned with the *truth* of alternative hypotheses in astronomy. He looks upon the truth of a hypothesis as something to be judged not merely in mathematical terms according to the adequacy and simplicity of a calculating device, but to be measured by its conformity to *all* the physical realities. At the very beginning of his *Epitome of Copernican Astronomy,* he flatly declares that "astronomy is part of physics." And in the opening pages of the fourth book, he insists that astronomy has not one, but "two ends: to save the appearances and to contemplate the true form of the edifice of the World." He follows this immediately by observing that, if astronomy had only the first end, Brahe's theory would be as satisfactory as that of Copernicus.

Early in his scientific career, before writing the *Epitome,* Kepler asserts that "one cannot leave to the astronomer absolute license to feign no matter what hypotheses." He complains that astronomers "too often ... constrain their thought from exceeding the limits of geometry."

It is necessary to go beyond geometry into physics to test the consequences of competing hypotheses which are equally good mathematically. "You must seek the foundations of your astronomy," he tells his fellow scientists, "in a more elevated science, I mean in physics or metaphysics."

Because Kepler thus conceives the task and truth of astronomy, Pierre Duhem in his great history of astronomy calls him a "realistic Copernican." Galileo also, Duhem thinks, was a realistic Copernican. "To confirm by physics the Copernican hypotheses," he writes, "is the center towards which converge Galileo's observations as an astronomer and his terrestrial mechanics."

Newton was the third member of this triumvirate. For him there remained the solution of the problem of deducing Kepler's formulation of the planetary orbits in a manner consistent with Galileo's laws of motion in the dynamics of bodies falling on the earth's surface. But the very posing of this problem itself depended on the insight that terrestrial and celestial mechanics can proceed according to the same principles and laws. That insight entailed the complete overthrow of the ancient physics, with its division of the universe into two distinct parts, having different kinds of matter and different laws of motion.

COPERNICUS, WHO, despite Osiander's apologetics, believed his theory to be true, did not himself face the great point at issue in the Copernican revolution—the material uniformity of the physical universe. We shall subsequently consider the question of the truth of astronomical hypotheses, but whether or not Copernicus and the Copernicans had *in their own day* a right to believe their theory true, it was the acceptance of the Copernican hypothesis as true which led Kepler and Galileo to deny the truth of Aristotelian physics.

If the earth is not at the center and stationary, then the basic doctrine of a natural direction in motion and a natural place of rest for the various elements is completely upset. If the earth is one of the planets, then anything true on the earth—or of the earth, such as Gilbert's theory of the magnetic fields generated by the earth's axial rotation—could be equally true of all the other planets.

"Read the philosophy of magnetism of the Englishman William Gilbert," writes Kepler; "for in that book, although the author did not believe that the Earth moved ... nevertheless he attributes a magnetic nature to it by very many arguments. Therefore, it is by no means absurd or incredible that any one of the primary planets should be, what one of the primary planets, namely, the Earth, is." Such a statement plainly shows that when the earth becomes a planet, as it does in Copernican theory, no obstacle remains to the assertion of a homogeneity between the earth and the other planets both in matter and motion. The old physical dualism of a supralunar and sublunar world is abandoned.

"Not the movement of the earth," Whitehead remarks, "but the glory of the heavens was the point at issue," for to assert the heavens to be of the same stuff and subject to the same laws as the rest of nature brings them down to the plane of earthly physics. That is precisely what Newton finally does when, in the enunciation of his Third Rule of reasoning in natural philosophy, he dryly but explicitly completes the Copernican revolution. Those "qualities of bodies ... which are found to belong to all bodies within the reach of our experiments, are," Newton maintains, "to be esteemed the universal qualities of all bodies whatsoever."

In the bifurcated world of ancient theory, astronomy had a very special place among the natural sciences, proportionate to the "glory of the heavens." But with Newton it could be completely merged into a general mechanics whose laws of motion have universal application.

In the 19th century, the unification perfected by Newton of terrestrial and celestial mechanics was complemented by a celestial and terrestrial chemical unification. By making a spectral analysis of the light coming from stars, including the sun, and comparing these spectra with those produced by terrestrial elements, it was shown that earthly and heavenly matter were in essence the same—a final refutation of Aristotle's idea that celestial and terrestrial matter are essentially different—the one incorruptible, the other not. One of the more remarkable discoveries of 19th-century astronomy was that of the element helium, which, as its name might suggest, was first identified in solar spectra rather than in studies of the earth.

But the unification of nature which Kepler began and Newton completed, when set against Aristotle's physics, may be even more radical. Newton's theory, because of the amazing way in which it covered the widest variety of phenomena by the simplest, most universal formula, is considered by Kant to have "established the truth of that which Copernicus at first assumed only as an hypothesis." But the larger contribution, in Whitehead's opinion, is "the idea of the neutrality of situation and the universality of physical laws ... holding indifferently in every part."

Whatever position we take today concerning the kind of truth which is possessed by hypotheses in mathematical physics, we now demand, in the spirit of the three Copernicans—Kepler, Galileo, and, above all, Newton—that physical hypotheses account at once for *all* the phenomena of the inanimate universe. Whatever the truth of modern as opposed to ancient physics, the Newtonian universe is so thoroughly established in our minds and feelings that, when we are reminded of the other universe in which men lived before the Copernican revolution, we tend to think it quaint, incredible, preposterous, superstitious, none of which it was.

Finally, from the point of view of our understanding of natural science itself, the astronomical controversy we have been considering is almost an archetypical model. It is necessary, of course, to appreciate the real achievement of Ptolemy as well as of Copernicus and Kepler in order to realize how genuine and difficult the issues were. Facts unknown to all of them may now have closed the dispute decisively, but issues in other spheres of modern science, almost identical in pattern with that great astronomical one, are not yet closed; and to the degree that we are able to reenact in our minds the motion of thought on both sides of the Copernican controversy, we can confront comparable scientific issues—still open—with open minds.

Darwin, for example, finds in the astronomical controversy a precedent to which he can appeal in the defense of natural selection against its adversaries. "The belief in the revolution of the earth on its own axis," he writes, "was until lately not supported by any direct evidence." But the absence of direct evidence does not leave a scientific theory without foundation, Darwin argues, if it has the power to explain several large classes of facts, which "it can hardly be supposed that a false theory would explain" in so satisfactory a manner. Darwin defends the theory of natural selection as having such power. To those who object that "this is an unsafe method of arguing," he replies—citing an example from astronomy— that "it has often been used by the greatest natural philosophers."

THE GREAT BOOKS of astronomy most lucidly exhibit the essential pattern of that kind of natural science which has, in modern times, come to be called "mathematical physics." Though that phrase may be modern, the ancients recognized the special character of the sciences which apply mathematics to nature and which consult experience to choose among hypotheses arising from different mathematical formulations.

Outlining a curriculum for liberal education, Plato, in *The Republic,* groups music and astronomy along with arithmetic and geometry as mathematical arts or sciences. In that context he treats them as pure mathematics. Astronomy is no more concerned with the visible heavens than music is with audible tones. Music is rather the arithmetic of harmonies, astronomy the geometry of motions. But in the *Timaeus* Plato turns mathematical formulas and calculations to use in telling what he calls "a likely story" concerning the formation and structure of the sensible world of becoming. Here, rather than in *The Republic,* we have, according to Whitehead, the initial conception of mathematical physics as well as deep insight into its nature and pattern.

Aristotle criticizes the notion of astronomy as a purely mathematical science. Just as "the things of which optics and mathematical harmonies treat" cannot be divorced from the sensible, so the objects of astronomy are also the visible heavens. "Astronomical experience," Aristotle writes, "supplies the principles of astronomical science." Yet, though its subject matter is physical and its method is in part empirical, astronomy, like optics and harmonics, takes the form of mathematical demonstration; and it is for this reason that Aquinas later calls such disciplines "mixed and intermediate sciences."

The development of astronomy from Plato and Aristotle through Ptolemy, Copernicus, and Kepler to Galileo and Newton thus constitutes an extraordinary set of "case histories" for the study of what J. B. Conant calls the "tactics and strategy" of science, and especially mathematical physics. But astronomy has one peculiar feature which distinguishes it from other branches of mathematical physics. It is empirical rather than experimental. The astronomer does not control the phenomena he observes. He does not, like the physicist, chemist, or physiologist, produce an isolated system of events by means of the laboratory arts.

Harvey comments on this aspect of astronomy when he proposes an experiment that will enable the physiologist to do what the astronomer cannot do, namely, deliberately prepare phenomena for examination by the senses. The astronomer must be content with the appearances as they are given. Defending psychoanalysis against attack "on the ground that it admits of no experimental proof," Freud points out that his critics "might have raised the same objection against astronomy; experimentation with the heavenly bodies is, after all, exceedingly difficult. There one has to rely on observation."

Since the invention of the telescope, the astronomer has had instruments of all sorts to increase the range and accuracy of his observations. As Francis Bacon points out, the telescope enabled Galileo to do more than improve upon the accuracy of prior observations. It brought within the range of observation certain celestial phenomena, hitherto imperceptible to the naked eye, such as the phases of Venus, the satellites of Jupiter, and the constitution of the Milky Way.

Concerning the last of these, Pascal later remarks that the ancients can be excused for the idea they had of the cause of its color. "The weakness of their eyes not yet having been artificially helped, they attributed this color to the great solidity of this part of the sky"; but it would be inexcusable for us, he adds, "to retain the same thought now that, aided by the advantages of the telescope, we have discovered in the Milky Way an infinity of small stars whose more abundant splendor has made us recognize the real cause of this whiteness."

BECAUSE IT IS a mixed science, both empirical and mathematical, astronomy advances not only with the improvement and enlargement of observation but also with new insights or developments in mathematics. Kant gives us striking examples of how the work of the pure mathematicians contributes to the advance of physics and astronomy. Their discoveries are often made without any knowledge of their application to natural phenomena. "They investigated the properties of the parabola," he writes, "in ignorance of the law of terrestrial gravitation which would have shown them its application to the trajectory of heavy bodies ... So again they investigated the properties of the ellipse without a suspicion that a gravitation was also discoverable in the celestial bodies, and without knowing the law that governs it as the distance from the point of attraction varies, and that makes the bodies describe this curve in free motion."

So amazing are such mathematical anticipations that Kant thinks Plato may be pardoned for supposing that pure mathematics "could dispense with all experience" in discovering the constitution of things. Whether or not Plato goes to this extreme, he does, in *The Republic,* seem to suggest the reverse of Kant's conception of the relationship between mathematics and astronomy. "The spangled heavens should be used as a pattern," he writes, "and with a view to that higher knowledge"—mathematics. Astronomy should be used to instigate discoveries in *pure* mathematics by suggesting good problems and by requiring formulations which transcend an interest in the truth about the heavens.

This twofold relation between mathematical discovery and empirical observation is present in the development of astronomy itself, and of all branches of mathematical physics. But there is another aspect of the relationship which must be taken into account if we are to consider the problem of truth in such sciences. The way in which mathematical formulations fit the phenomena measures the truth of rival hypotheses with respect to the same reality.

The logic of such verification has already been suggested in the discussion of the geocentric and heliocentric hypotheses. It is further considered in the chapter on HYPOTHESIS. To be satisfactory, a hypothesis must—in the language used ever since Simplicius—"save the appearances," that is, account for the relevant phenomena. But two hypotheses (as for example the geocentric and heliocentric) may, at a certain time, do an equally good job of saving the appearances. Then the choice between them becomes a matter of the greater mathematical elegance of one than the other.

That, however, does not give the mathematically superior theory a greater claim to truth. So far as reality is concerned, it is only, in Plato's words, "a likely story"; or as Aquinas points out with reference to the geocentric hypothesis, "the theory of eccentrics and epicycles is considered as established because thereby the sensible appearances of the heavenly movements can be explained; not however, as if this reason were sufficient, since some other theory might explain them."

Two hypotheses may be equally satisfactory for the range of phenomena they were both devised to fit. But only one of them may have the quite amazing virtue of fitting other sets of observations not originally thought to be related to the phenomena for which the hypothesis was devised. The word "consilience" has been used to name the property of a hypothesis which, in addition to saving a limited field of appearances, succeeds in fitting many other phenomena which seem to have become related—to have *jumped together* under its covering explanation. The heliocentric hypothesis, as developed by Newton's laws of motion and theory of gravitation, certainly has this property of consilience to a high degree, for it covers both celestial and terrestrial phenomena, and a wide variety of the latter.

Is the heliocentric hypothesis true then? If the truth of a hypothesis depends on the range of the phenomena it fits or saves, it might seem to be so, for by its consilience it accounts for phenomena that the Ptolemaic theory cannot handle. But though this may cause us to reject the unsuccessful hypothesis, does it establish beyond doubt the truth of the successful one? Or, to put the question another way, is not our judgment here a comparative one rather than absolute? Are we saying more than that one hypothesis is more successful than another in doing what a hypothesis should do? Are we logically entitled to regard that success as the sign of its exclusive truth, or must we restrict ourselves to the more modest statement that, as the better hypothesis, it simply tells a more likely story about reality?

A STRIKING FEATURE of contemporary astronomy is the role evolution plays in it. Stars, it is now argued, are "born" and then "die." More precisely, stars are formed by the gravitational clumping of proto-stellar matter and may, for example, end their existence as black holes or white dwarfs. The cosmos itself is now thought to evolve from a singular explosive state into a highly uniform, frigid, dilute gas.

The last attempt to formulate a non-evolving cosmology was the steady state theory of Sir Fred Hoyle, Hermann Bondi, and others. There was a time when Einstein himself favored some sort of non-evolving cosmology. This fell out of favor with him in the late 1920s with the discovery by Edwin Hubble that the universe is expanding.

In the 1940s George Gamow and his collaborators attempted to give an account of the formulation of the elements during the first four minutes following the primeval explosion, the so-called "Big Bang." In the course of this work, they noted that a remnant of that explosion would be an ambient background of radiation at a temperature of a few degrees above absolute zero. In the 1960s, this radiation was discovered. Its discovery put an end to a non-evolutionary cosmology, such as the steady state theory. At the present time, there is a partial merger between astronomy and cosmology, and the combined discipline is one of the most vigorous contemporary sciences.