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KEPLER AND THE ORIGIN OF MODERN SCIENCE

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It is well-recognized that the creation and development of modern science was the work of many geniuses. This paper is an attempt to highlight the contribution of Kepler to this momentous achievement. I point out that this process involved the creation of a new perspective, the emergence of new concepts, the discovery of important laws of nature, and the development of a strong scientific method. This study claims that in all these four aspects Kepler made substantial contribution to entitle him to be counted among the founders of modern science.

The creation of the new perspective involved a number of fundamental shifts: from a geocentric to a heliocentric world, from the metaphysical to the physical, from an emphasis on the qualitative to the quantitative, from a dichotomized to a unified universe, and from "saving the phenomena" to explaining them. Kepler played a central role in developing key scientific concepts like force and mass. This paper traces the evolution of these concepts in Kepler's thought. While discussing the significance of Kepler's laws, their possible influence on Newton's work is also touched upon. The Hypothetico-Deductive method is arguably the most widely and effectively used method in science. Much has been written about the contribution of Galileo and others in developing and promoting this method. This study points out that Kepler also used it successfully and contributed to its development. In short, Kepler was one of those giants on whose shoulders Newton could confidently stand as he surveyed the widening expanses of classical physics.

Key-words : Copernican revolution, Kepler's laws, New science, Scientific method.

The creation and development of modern science is undoubtedly the most significant accomplishment of humans. Modern science has worked wonders in the field of medicine and technology; it has transformed the way we look at the universe. Such great accomplishments can never be done by a single individual. Indeed, modern science is the work of great geniuses. Johannes Kepler certainly was one of those giants although till recently he was very much underrated, living under the shadow of scientific giants like Galileo and Newton. This paper is an attempt to highlight some of the outstanding contributions of Kepler to science in general and to astronomy in particular. It seems to me that when we really take into account both the quantity and quality of Kepler's contributions to science, we are led to conclude that the true scientific revolution was more Keplerian than Copernican.

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Several other scholars also have arrived at the same conclusion. Norwood Hanson talks of a "Copernican disturbance," and a "Keplerian revolution;" Jürgen Mittelstrass argues for a "Keplerian revolution" rather than a "Copernican revolution."

Life and Works of Kepler

Kepler was born in 1571 in Weil der Stadt, Germany, in a Lutheran family. Though physically weak all through life, he was gifted with a sharp intellect and found his way to the prestigious University of Tübingen with the intention of becoming a Lutheren minister. It was here that he made his first contact with the Copernican theory through the astronomer Michael Maestlin, who was a secret sympathizer of the new theory. In 1594 Kepler took up the job of a teacher of mathematics and astronomy in a high school at Graz, where he published his first book the *Mysterium Cosmographicum* in 1596. Religious persecutions and financial troubles drove him in 1600 to work under Tycho Brahe, the greatest observational astronomer of the century, in Prague. After the death of Tycho in 1601 he became the imperial astronomer of Emperor Rudolph. While in Prague in 1604 he published the *Astronomia Pars Optica* and in 1609 the *Astronomia Nova*, his most important book, which describes the discovery of his first two laws of planetary motion. Later he moved to Linz, Austria, where he wrote the *Harmonices Mundi*, which announced the third law of planetary motion. Kepler's most systematically presented book the *Epitome* was also published here during the years 1618-1621. At Ulm in 1627 he published his last great work the *Tabulae Rudolphinae*. He died on November 15, 1630, in Regensburg.

Keplerian Program

Although today the accepted goal of science is to understand the nature and operations of material nature on the basis of observational data, the avowed goal of Kepler's scientific work was far broader and deeper. He wanted to "read the mind of God" and it is this deep-felt desire that impelled him to give up his earlier ambition of becoming a Lutheran minister in order to embrace astronomy. He wanted to discover the profound plan of God so that he could glorify the immense wisdom of the Creator. In the concluding section of the *Mysterium Cosmographicum* he wrote:

> Now, friendly reader, do not forget the end of all this, which is the conception, admiration and veneration of the Most Wise Maker. For it is nothing to have progressed from the eyes to the mind, from sight to contemplation, from the visible motion to the Creator's most profound plan, if you are willing to rest there, and do not soar in a single bound and with complete dedication of spirit to knowledge, love and worship of the Creator ...... [1]

This religious concern was the primary motivating factor that led him to two theories which eventually turned out to be incorrect: the polyhedral theory of the structure and number of planets and the harmonic theory of planetary motion. Kepler wanted to find out why there were only six planets[2] and what accounted for the observed spacing between them. To his great surprise and immense joy the answer came to him on 9/19 July, 1595, in the form of the polyhedral theory when he was delivering a lecture to his confused students. He found that he could explain the arrangement of the six planets in the solar system in terms of the five regular solids that were nested within a series of concentric spheres. He argued that by placing appropriately the five regular solids within concentric spheres, one could closely approximate the spacing of the planets. Since he believed that God was a geometer, who created the universe in accordance with the principles of geometry, he was convinced that this was the divine plan for the creation of the world. Although the agreement between the theory and the observed data was not satisfactory enough, he continued to believe in this theory with the firm hope that more accurate data would yield better results.

Kepler believed that God was not only a dry geometrician, but also a lover of aesthetic beauty, of harmony, especially musical harmony. According to him, God's creation of the universe involved not only laws of geometry but also those of harmony. The different parts of the universe were related to each other by definite harmonic ratios. In his *Harmonices Mundi* he applied the considerations of musical harmony to the study of the structure and laws of nature. His investigations revealed that the ratios of the angular velocities of the planets (as observed from the sun) at the extremities of their orbits were the basic musical intervals: 4/5 (major third) for Saturn, 5/6 (minor third) for Jupiter, 2/3 (perfect fifth) for Mars, 15/16 (major semitone) for Earth, 24/25 (minor semitone) for Venus, and 5/12 (octave plus a minor third) for Mercury. In his view the discovery of this cosmic music which the Creator sang and still sings was of the utmost significance because it provided him with the first genuine model of the universe.

Today we know that both these theories were wrong, thanks to the discovery of Uranus, Neptune, and Pluto, and developments in planetary astronomy. It is possible that the hitherto-unexplained Titius-Bode[3] law was inspired by Kepler's polyhedral theory since one easily notices an analogy between the two. For Kepler the harmonic theory had concrete scientific application because he argued that it could be used to calculate the age of the universe, or at least of the solar system.[4] He deduced from this theory by calculation the number of years needed for two planets to come into consonance. The same procedure was used for three planets and finally for all the planets in the solar system. He identified the starting moment of the universe with the instant of consonance among all the planets. Although here he did not carry out the actual calculation, he gave directions for it.[5] Indeed Kepler was the first scientific cosmologist to attempt to compute the age of the universe by a scientific method of the day.

The fact that some of his theories turned out to be wrong in no way disqualifies Kepler from being one of the founders of modern science. Modern research on the history and philosophy of science has shown that scientists are scientists not because they get everything right, but because they have the basic scientific spirit, a spirit that is open but critical, that never fears to speculate, that ever dares to subject the speculations to severe tests. This spirit Kepler always had. The rest of this paper will discuss the outstanding contributions of Kepler towards the origin and development of science.

Creation of a New Perspective

The advent of modern science involved the creation of a new perspective or world view, the emergence of new concepts, the discovery of new laws, and the development of a new method. I will argue that in all these areas Kepler made substantial contribution to deserve to be counted among the founding fathers of modern science.

Thomas Kuhn and others have convincingly argued that any scientific revolution necessarily involves the creation of a new perspective. This indeed happened in the case of modern science in the sixteenth and seventeenth centuries. We can identify a number of fundamental shifts responsible for bringing about this radical change of perspective.

From a Geocentric to a Heliocentric World

The most significant event in the scientific revolution was the introduction by Copernicus of heliocentrism in place of the old geocentrism. But the heliocentrism of Copernicus left much to be desired. As Dreyer rightly points out, Copernicus did not produce what is popularly meant by the "Copernican system."[6] According to Kuhn, "Most of the essential elements by which we know the Copernican Revolution – easy and accurate computations of planetary position, the abolition of epicycles and eccentrics, the dissolution of the spheres, the sun a star, the infinite expansion of the universe – these and many others are not to be found anywhere in Copernicus's work."[7] The original Copernican idea would probably have remained still-born, had not other geniuses like Kepler taken it up and developed it.

Two points are central to the Copernican system: the centrality of the sun and the reality of the system. Unfortunately in both these points Copernicus fell short and it was Kepler who really remedied these deficiencies and brought credibility to the system. The system presented in the *De Revolutionibus* was not a truly heliocentric system. At best the sun was the geometrical center only, it certainly was not the dynamic center of the universe.[8]

Although Copernicus was primarily instrumental in banishing geocentrism from astronomy, the ghost of geocentrism persistently haunted his system: the earth continued to have a prominent place in it, with accompanying problems. For instance, he assigned a special significance to the center of the earth's orbit. The eccentricities of all the planets, except the earth, were measured from this point, only the eccentricity of the earth's orbit was measured from the sun. Similarly, all the orbital planes of the planets intersected at this center of the earth's orbit. Furthermore, in his system the earth's sphere, unlike the spheres of the other planets, had no thickness, since its path was everywhere equidistant from the mean sun (i.e., the center of the earth's orbit). Kepler right at the outset recognized that many of the problems pestering Copernicanism had their source in this halfhearted heliocentrism and urged for a wholehearted heliocentrism. He shifted the point of reference to the body of the sun. He also demanded that the body of the sun be the point of interesection of planetary orbital planes. Besides, he identified the sun as the cause of planetary motion and the source of force needed to drive the planets around. Indeed, it was Kepler who made the sun both the geometrical and the dynamic center of the system and so only the Keplerian system could be called a truly heliocentric system.

Secondly, although Copernicus believed his model to be a true representation of the universe, his commitment to realism raised serious doubts. The *De Revolutionibus* left ample room for Osiander and like-minded scholars to doubt the seriousness of his realism. For instance, in his dedicatory letter to Pope Paul III Copernicus wrote: "So I should like your Holiness to know that I was impelled to consider a *different system of deducing* the motions of the universe's spheres for no other reason than the realization that astronomers do not agree among themselves in their investigations of this subject."[9] Obviously, here he himself gives evidence of instrumentalism – he was looking for a "different system of deducing the motions." Kuhn translates the phrase as a "method of computing the motions,"[10] which is not inaccurate in this context. Neugebauer, referring to Osiander's preface says: "I realize that one is supposed to be disgusted with Osiander's preface which he added to the *De Revolutionibus* (in keen anticipation of the struggle of the next generations), in which he, in the traditional fashion of the ancients, speaks about mere hypotheses' represented by the cinematic models adopted in this work. It is hard for me to imagine how a careful reader could reach a different conclusion."[11]

Perhaps the greatest source of doubt about the realism of Copernicus came from his generous use of epicycles. Any system that relied on epicycles would find it difficult, if not impossible, to make a convincing claim for realism. The many epicycles used by Copernicus has led some scholars to call him "a more orthodox epicyclist' than Ptolemy himself, as he rejected the equant of the latter."[12] It is claimed that

Copernicus reduced the number of epicycles from eighty to thirty four. This claim is contested by scholars, who point out that the Ptolemaic system of Peurbach in his *Theoricae novae Planetarum* could manage with less epicycles. That Copernicus felt very comfortable with epicycles was clear from the concluding part of his *Commentariolus* : "Thus Mercury runs in all on seven circles, Venus on five, the earth on three, and round it the moon on four, lastly Mars, Jupiter and Saturn on five each. Thus altogether 34 circles suffice to explain the whole construction of the world and the whole dance of the planets."[13] Kepler considered such devices totally unacceptable and unnecessary. He made this point absolutely clear when he declared to Fabricius: "Nothing courses in the heavens except the planetary bodies themselves, – neither orbs nor epicycles."[14] He cleared the Copernican astronomy of all such epicycles, thereby redeeming its claim to being the real picture of the universe. It may be noted that Galileo was not disturbed by the presence of epicycles in the Copernican system; in fact, he persistently supported its use.[15]

Another main deficiency of Copernicus was his failure to provide a physics for the new system. The system he wanted to replace had both the physical and the astronomical aspects, but the new theory he proposed touched mostly only the astronomical part. In the absence of a satisfactory physics the new system remained very much a geometrical model and it raised many new problems, which the system was unable to handle. For instance, if the earth moves, from where does the required force come? Copernicus's explanation of the motion of the earth in terms of the sphericity of the earth was nothing but a rehearsal of the old Aristotelian argument. Kepler, on the other hand, assiduously worked to develop a physics of the heavens. He was the first to ask the fundamental question "*A quo moventur planetae* (What is it that makes the planets move")? His long and extensive investigation correctly identified the sun as the source of force and the cause of planetary motion. His account of the solar propulsion of the planets by means of the immaterial species turned out to be incorrect. But it cannot be denied that he made a pioneering attempt to develop a physics for the new system.

Change from the Metaphysical to the Physical

A deemphasis on the metaphysical and an emphasis on the physical was another principal characteristic of the scientific revolution. No one can deny the pre-eminent place of metaphysics in Pre-Copernican science, thanks to the enduring influence of Plato and Aristotle. In the pre-Copernican era often metaphysical principles determined and controlled the nature and direction of science. The principle of circularity, which went unchallenged till the time of Kepler, was a supreme example of the power of metaphysics to hypnotize the minds of scholars and non-scholars alike. This principle stipulated that all true motion in the celestial world had to be circular, irrespective of observations to the contrary. Nobody challenged this principle for almost three thousand years; neither Copernicus, nor even the great revolutionary Galileo. When Kepler at last made the historic break in 1609 in his *Astronomia Nova*, his contemporaries either ridiculed him or refused to take him seriously. He deviated from the traditional path because his goal was to give "a physics of the heavens in place of a theology of the heavens or a metaphysics of Aristotle."[16]

Scientific knowledge for Aristotle was knowledge in terms of the immutable essences. Since the senses have access only to accidents like color, taste, texture, etc., sense observation could not have been the crucial criterion in that science. Scientific knowledge involved logical deductions from certain presuppositions assumed to be true of the universe on the basis of logical rather than physical principles.[17]

It will be wrong to claim that Kepler's science was free from all metaphysics. The latter certainly had a role to play in his science,[18] but a limited one. They had no special supremacy in his science, they could be overruled by observations. This point is made convincingly clear by his emphasis on observation and physical explanation.

A. *Importance of Observation*

Kepler considered observation uniquely important in his system. In this context Max Caspar has the following to say: "As daring and rich in fantasy as he was in his speculations about the universe, just as thoroughly did he now proceed, taking no step without gathering authorization and confirmation from the observations. Indeed, while following his Mars researches, one almost gets the impression that sometimes he deals with individual tasks and proofs out of pure delight and pleasure in the observations."[19] He considered precise and quantitative observations crucial for scientific work. "Without appropriate experiments I conclude nothing,"[20] he affirmed. Again, he wrote to David Fabricius, his faithful and persistent correspondent and critic: "Hypothesis must be built upon and confirmed by observations....."[21] In the *Astronomia Nova* he called observations "*fidissimi duces* (most reliable guides)."[22] When his theory was attacked by others, his major defense consisted in referring his opponent to observational data. He asked: "Is there anything in astronomy more certain than the observations either of the Sun or Mars? I make judgments from these."[23]

He himself made many observations, despite his own visual problems and the lack of accurate and advanced instruments. Copernicus and others tried to explain away the failure to observe stellar parallax, on the plea that the stars were too far from the earth for their apparent motion to be noticed by us. But Kepler insisted on observing it and was convinced that it would be observed at some future time.

How much he valued accurate observations is well-manifested by his willingness to make exceptions to many other principles he otherwise so zealously cherished in life. He was deeply attached to the principle of circularity; but he gave it up when observations convinced him that the Martian orbit deviated from the circle.

B. *Physical Explanation*

In contemporary science explanation in terms of physical, real factors has become so routine that we can hardly appreciate the significance of Kepler's contribution. Gingerich points out that "Kepler was the first and until Descartes the only scientist to demand a physical explanation for celestial phenomena."[24]

It is difficult to give a precise and clear-cut idea of the physical because Kepler did not give any formal definition for it. Basically, for Kepler a physical explanation was explanation in terms of matter and forces. For instance, consider his explanation of planetary motion in terms of the effluvia from the body of the sun. This emanation was like a magnetic force whose effects could be explained, although its cause remained unknown. It could account for the observed motion of the planets around the sun.

This insistence on physical causes to explain natural phenomena was something unprecedented, as was clear from the practice of scientists or natural philosophers up to that time. Perhaps the most eloquent testimony to its novelty came form the stiff opposition Kepler had to face from friends and foes alike. Fabricius voiced his strong disagreement in no uncertain terms in several of his scholarly letters to Kepler. Strongly influenced by the voluntarism of his day, he argued that God's will was responsible for the different events and phenomena in the universe and so their explanation was to be sought in God's will rather than in any physical causes, which were responsible only indirectly, if at all.

Not even Maestlin, a rather liberal and open-minded crypto-Copernican, who encouraged Kepler in so many ways and to whom Kepler had the profoundest respect, appreciated this emphasis on physical explanation. As Kepler informed Peter Crüger, professor of mathematics in Danzig, "Maestlin used to laugh about my endeavors to reduce everything, also in regard to the Moon, to physical origin. In fact, this is my delight, the main consolation and pride of my work, that I succeeded in that...."[25] Maestlin was more emphatic in his letter of September 21, 1616, when he said that "physical hypothesis..... would more likely confuse than instruct the reader."[26] Thus even years after the publication of the *Astronomia Nova* a liberal-minded Maestlin found Kepler's new idea utterly foolish and unjustified. Clearly Kepler had departed decisively from the traditional path.

C. *The Mechanical Philosophy of Nature*

The mechanical philosophy of nature was the natural by-product of any system that emphasized physical explanation. This philosophy, which cooriginated with modern science, looked at our universe fundamentally as a machine rather than an organism. It proposed to explain physical nature, if not nature in general, in terms of matter in motion and its interaction. More specifically it postulated that there were four fundamental concepts by which every thing in the universe could be accounted for: matter (mass), space, time, and force (interaction). Although traditionally Kepler is not given much credit for originating the mechanical philosophy of nature, an unbiased look at his contributions reveals that he too must be counted among the founders of this philosophy, because he not only helped considerably in the development of the basic concepts of mass and force but also was the first among modern scientists to look upon the universe as a machine. This was clear from his letter to Herwart: "My aim is to show that the heavenly machine is not a kind of divine, living being, but a kind of clockwork...., insofar as nearly all the manifold motions are caused by the most simple, magnetic, and material force, just as all motions of the clock are caused by a simple weight."[27] He also demanded that an adequate scientific explanation should be given in terms of real, physical forces seated in matter. This was the very same demand made by mechanical philosophy. All these considerations go to show that Kepler had a significant role to play in the birth of the mechanical philosophy of nature.

Emphasis on the Quantitative Rather than the Qualitative

Emphasis on the quantitative or quantifiable aspect of reality is a basic characteristic of modern science. In practice this means that mathematics plays a central role in modern science. Use of mathematics has become so common in science that we often forget that this was not at all the case in Aristotelian science. Aristotle had banned the use of mathematics on the plea that mathematics could yield only knowledge in terms of quantity which is an accident, whereas scientific knowledge will have to be in terms of essences.

Kepler was a firm believer in the power of mathematics to unravel the mysteries of the universe. According to him, "human understanding seems to be such from the law of creation, that nothing can be known completely except quantities or by quantities."[28] He believed that "since God created everything in the whole world in accordance with the norms of quantity, God has given to man a mind which can comprehend quantity. For as the eye is created for colors, the ear for sounds, so also is the mind created for no other reason than to understand quantities. It will perceive an item more accurately, the closer it is to pure quantities, as though to its origin. Conversely, it will remain the more in darkness and error, the more it distances itself from quantities."[29] He used mathematics generously in his research. He was the first mathematical scientist in the modern sense.

SHIFT FROM A DICHOTOMIZED TO A UNIFIED UNIVERSE

The old world view emphasized a sharp distinction between the celestial and terrestrial worlds, obeying two different sets of laws and criteria. Kepler aimed at demolishing this separation and building up a unified cosmic view and a unified science. His was the first serious and constructive effort in this direction. He applied the laws of mechanics, hitherto believed to be applicable only to the terrestrial world, in the investigation of the motion of the heavenly bodies, thereby initiating the search for a single universal law governing both worlds. This move led to a redefinition of the domain of physical science as comprising both the terrestrial and the celestial.

SHIFT FROM "SAVING THE PHENOMENA" TO EXPLAINING THE PHENOMENA

Following the Platonic principle, traditional astronomy aimed at "saving the phenomena," i.e., accounting for the observed irregular motion of the planets in terms of uniform, circular motion.[30] True motion was identified with uniform circular motion. It was not concerned about going beyond the observed to investigate the underlying reality. But we know that modern astronomy and science are not satisfied with such a limited and superficial objective. Astronomy is not content with calculation and prediction of phenomena, it wants to delve deep to learn about the reality within. Kepler already in the seventeenth century insisted on this point. According to him, "the astronomer ought not to be excluded from the community of philosophers who inquire into the nature of things. One who predicts as accurately as possible the movements and position of the stars performs the task of astronomy well. But one who, in addition to this, employs true opinion about the form of the universe performs it better and is held worthy of greater praise."[31]

The Aristotelians and other guardians of tradition certainly did not appreciate this trespassing into the forbidden territory. To them Kepler had a few harsh words to say: "O wretched Aristotle! Wretched is that philosophy of his in the part said to be most excellent, if astronomers become such faithless witnesses on philosophical questions."[32] Kepler thus redefined the role of astronomy as not just saving the phenomena but also explaining them.

This change from "saving the phenomena" to explaining them in turn led to a shift from the kinematic to the dynamic approach in astronomy. The tradition of "save the phenomena," being concerned with a kinematic or mathematical approach, had no real concern for the physical or dynamical aspect of the phenomena. The different celestial bodies were looked upon as mathematical points, bereft on any physical significance. Kepler strongly departed from this tradition and advocated a true dynamic approach. For him planets were real material bodies, moving under the influence of real, physical forces. His work transformed what was a pure mathematical or geometrical exercise into a true scientific enterprise. He is rightly honored as the father of modern astronomy.

This shift from a pure kinematic to a physical astronomy involved a causal approach. Astronomy could no more remain at the superficial level of appearances only, it had to delve deep into the forces responsible for such appearances. Modern science is characterized by an emphasis on efficient or mechanical causality, rather than formal and final causality, as in the case of the Aristotelian science. Although at times Kepler followed the Aristotelian tradition, he initiated the practice of emphasizing the efficient and mechanical causes in the study of natural phenomena.

These developments gave rise to another important change as well: a shift from the "why" question to the "how" question in the study of natural phenomena. The Aristotelian science with its emphasis on formal and final causes usually addressed the "why" of things, whereas modern science focuses its attention on the "how" of things. For instance, in the case of a clock the scientific question is not why it shows time, rather how it is designed and assembled so as to show accurate time. The inner structure and operation of the machine becomes the focus of the scientist's attention. Kepler with his emphasis on causal explanation of phenomena was pioneering this important shift of focus. for instance, while studying planetary motion he wanted to know how the sun brought about the regular and harmonious movement of the planets. He wanted a celestial physics in place of the Aristotelian celestial theology or celestial metaphysics.

Kepler's new approach entailed other important consequences also. Since the subject under investigation was a true body performing true motion, its exact distance from the central body, its exact velocity, and actual path became important. Earlier these items were deemed unimportant. As Koyre remarks, in the old astronomy "it was not the orbits of the planets that mattered, but only the angular distances between the phenomena."[33] Since the old astronomy was unable to determine precisely the linear distances of the planets from the sun, it was not interested in computing the orbits accurately. Hence "the orbit of the planet had no real existence for pre-Copernican astronomy. It interested no one. A study of the orbit, and a determination of the distances of the planet from the sun were radical innovations."[34] In short, Kepler laid the foundation for a new astronomy.

The Emergence of New Concepts

Since concepts are the foundation of any system, the new science required the development of new concepts. Kepler played a central role in the creation and development of key scientific concepts like force, mass, inertia, etc. The process of concept formation can be divided into three stages: conceptualization, systematization, and formalization. Kepler's contribution was mainly in the first stage.

A. *The Concept of Force*

Perhaps no other concept is more central to classical physics than that of force. Although in the hands of Newton it attained its modern form, it went through a period of progressive evolution, thanks to the significant contributions of many scientists before Newton. Many scholars have acknowledged the outstanding contribution made by Kepler in this process. According to Max Jammer, Newtonian force had its origin in the ideas of Kepler.[35] Koestler thinks that Kepler's was "the first serious attempt to explain the mechanism of the solar system in terms of physical forces."[36] There is no doubt that Kepler fell far short of the Newtonian idea. But "what matters is not the result achieved.... but his new approach, his search for a *quantitative* definition of force."[37]

Kepler developed his ideas on gravitational force in the context of explaining how the sun moved the planets. According to him, from the body of the sun some kind of *species immateriata* emanated. This immaterial species like the spokes of a wheel dragged the planets around the rotating sun.

For Aristotle gravitation was a *locational effect,* in the sense that it was determined by a certain specific location.[38] Kepler, on the other hand, at first gave an animistic notion of the gravitational force; it involved a soul animating the celestial bodies and directing their proper motions. He moved away from the metaphysical to an animistic or psychical conception. Later there was a move to deanimate this force. In his letter to Herwart on March 28, 1605 he wrote: "If we were to place the earth at rest in some place and bring near to it a larger earth, the first would become a heavy body in relation to the second and would be attracted by the latter just as a stone is attracted by the earth. Gravity is not an action but a passivity of the stone which is attracted."[39]

In Kepler we notice also a move towards universalizing the gravitational force, although not to the extent Newton would do later. According to Kepler, this force was not the prerogative of one body (the earth) only. He emphasized the mutuality of this force: not only the earth exerted a force on the stone, there was also a simultaneous force exerted by the stone on the earth.[40] He went further to assert that the moon also possessed the same kind of force. This was clear from his explanation of the tides. From his careful study of the phenomenon of the tides he noticed a temporal coincidence of the tides with certain lunar positions. This led him to conclude that the moon had a vital role to play in causing the tides. Galileo blundered when he ridiculed Kepler's intuition about the formation of the tides. There is clear indication that Kepler attributed the same kind of force to the sun also, as is clear from his *Somnium,* no. 202: "But the causes of the ocean's swell seem to be the bodies of the sun and the moon which attract the waters of the sea by a certain force similar to magnetism. The body of the earth also attracts its own waters unto itself, by a force which we call gravity."[41]

Obviously the sun, the moon, and the earth all possess the same gravity. Hence here we see Kepler breaking out of the old theory of attraction among kindred bodies only, to embrace a universal, though limited, theory of gravitation. All these considerations lend support to Jammer's view that "Kepler had already conceived the universal character of attraction, an idea generally attributed to Newton." Hence "it is Kepler and not Newton who has to be credited with having suggested that the familiar behavior of falling bodies and the majestic sweep of the moon in its orbit were all part of the same great scheme. Newton, of course, was the first to demonstrate clearly the correctness of this assertion."[42]

Kepler added another important contribution to the development of the modern idea of gravitation when he insisted that this force had a material base, as opposed to a metaphysical or animistic base. In his letter to Brengger, he clearly stated that the force was "material and corporeal."[43] In the *Astronomia Nova* he made this point even clearer: "Gravity is a mutual corporeal disposition among kindred bodies to unite or join together."[44] Kepler agreed with Gilbert to conclude that "it is in bodies themselves that acting force resides, not in spaces or intervals."[45]

But Kepler clarified that having a material base did not mean that it itself was something material like apples and oranges. The gravitation he talked of was an immaterial species (*species immateriata*). Though immaterial, it was not purely spiritual, it was corporeal because it resided in the material body. This emanation or species "flowed from the sun's body out to its distance without the passing of any time..."[46] The *species* was therefore independent of time in the sense that it moved without the passage of time. It lacked weight too.[47] But he insisted that, despite its immateriality and weightlessness, it did not possess infinite velocity.[48]

Kepler then magnetized this force. "The planets are magnets and are driven around by the sun by magnetic force."[49] Since magnetism was considered a physical force, this move confirmed the physical nature of this force.

Kepler's claim about the mathematizability of this force also contributed significantly to the development of the modern idea of gravitation. As he put it, "for we see these motions taking place in space and time and this virtue emanating from its source and diffusing through the spaces of the universe, which are all mathematical [geometrical] realities. From this it follows that this virtue is subject also to other mathematical laws (*necessitatibus*)."[50] We can conclude that the Keplerian force was a quantifiable, immaterial but corporeal species, seated within a material body. Thus he had taken a giant step away from the old traditional view and even from his own view held in the first edition of the *Mysterium Cosmographicum*. He made sure that his readers captured this evolution of his idea when he wrote the important note in the second edition of the *Mysterium* :

> If for the word "soul" you substitute the word "force," you have the very same principle on which the celestial physics is established in the *Commentaries on Mars*, and elaborated in Book IV of the Epitome of Astronomy. For once I believed that the cause which moves the planets was precisely a soul, as I was of course imbued with the doctrine of J.C. Scaliger on moving intelligences. But when I pondered that this moving cause grows weaker with distance, and that the sun's light grows thinner with distance from the sun, from that I concluded, that this force is something corporeal, that is, an emanation which a body emits, but an immaterial one.[51]

Although Kepler's idea of force, with its corporeal and quantifiable nature, was non-Aristotelian, it differed from the Newtonian notion of force in several respects. First of all, this force was proportional to the reciprocal of the distance, rather than the square of the distance, as in the case of Newton's law of gravitation. Actually in the beginning Kepler had conjectured that the intensity of the force varied inversely as the square of the distance. But he soon rejected it believing that the force spread only in the plane of the planetary orbits, proportional to the velocity of the moving object. But as Jammer points out, "irrespective of this error, it was Kepler who transformed the concept of force from its Platonic form and interpretation to an essentially rational concept."[52] Again, Kepler's force was a tangential, pushing force propagated from the body of the sun in straight lines producing velocity, whereas the Newtonian idea was of central force producing acceleration. Furthermore, Newtonian force could act on bodies at a distance without material contact, whereas Kepler still adhered to the Aristotelian idea of contact forces. Despite all these differences Kepler's contribution was significant. As Mittelstrass points out, "the gradual genesis of the concept of force in Kepler effects a conceptual orientation which, even though it remains incomplete in the end, runs through all the stages of pre-modern research on *causal hypothesis* and thus makes a decisive contribution to the articulation of the conceptual framework of physics."[53]

B. *The Concept of Mass*

Kepler's name is closely associated with the development of the concept of mass also. According to Jammer, "Galilean physics did not work out a distinct formulation, nor did it even establish an explicit recognition of what proved to be, apart from length and time, the most fundamental concept in classical physics. It was Keplerian astronomy that filled the lacuna and thus completed the foundation on which Newton's genius could build the majestic structure of classical mechanics."[54]

No doubt Kepler borrowed some of his ideas from his predecessors like Oresme, Buridan, etc., who spoke of *inclinatio ad quietem* (natural tendency to rest or resist motion). But they were referring to voluntary forces, not subject to physical laws, because for them the moving forces of the celestial spheres were spiritual intelligences. In other words, their concept was very much metaphysical, but Kepler turned it into a scientific concept, at least as far as the science of his day permitted.

Kepler's concept of mass also evolved in the context of explaining the mechanism of planetary motion. As in the case of the concept of force, this concept of mass also underwent an evolution not only in the history of science but also in Kepler's own thought. In the beginning he talked of a "plumpness" of all material bodies, which obstructed motion. "All corporeal stuff or matter in the whole world has this virtue, or rather vice, that it is plump and clumsy to move itself from one place to another."[55] According to his *De stella nova* in *Pede Serpentarii*, matter had an inherent tendency to resist motion and to remain at rest.[56] In the *Tertius interveniens* also the same idea was expressed: "I, for my part, say that the celestial spheres have the property of abiding at any place in the heavens wherever they are found, unless they are drawn along."[57] The *Epitome* too affirmed this point: "Every celestial sphere, because of its materiality has a natural inability to move from place to place, a natural inertia or rest whereby it remains in every place where it is set by itself."[58] His extensive and careful study of planetary motion revealed that inertia was something like weight and it influenced the motion of planets. He concluded:

> If the matter of celestial bodies were not endowed with inertia, something similar to weight, no force would be needed for their movement from their place; the smallest motive force would suffice to impart to them an infinite velocity. Since, however, the periods of planetary revolutions take up definite times, some longer and others shorter, it is clear that matter must have inertia which accounts for these differences.[59]

Scholars like Jammer point out that this passage contains the germs of the second law of Newton in a qualitative way.

The inertia Kepler talked about had both a static aspect, i.e. inability to transport itself from place to place, and a dynamic aspect, i.e., it 'fought back against," (*repugnans*) was repugnant to motion imparted from outside. This dynamic aspect was most conspicuous in the case of planetary motion under the influence of the sun's *species*. "The transporting power of the sun and the impotence of the planet or its material inertia fight with each other."[60] In a note in the second edition of the *Mysterium Cosmographicum*, he pointed out that this resistance to motion depends on the quantity of matter.

> Clearly the bodies of the planets in motion, or in the process of being carried round the sun, are not to be considered as mathematical points, but definitely as material bodies, and with something in the nature of weight (as I have

> written in my book *On the New Star*), that is, to the extent to which they possess the ability to resist a motion applied externally, in proportion to the bulk of the body and the density of its matter.[61]

Kepler argued that this mass, like force, is quantifiable. Describing the property of mass or *moles*, as he called it, he wrote: "If two stones were placed in any part of the world, near each other yet beyond the sphere of the influence of a third cognate body, these two stones, like two magnetic bodies, would come together at some intermediate place, each approaching the other through a distance in proportion to the mass of the other."[62] The distance each stone will move depends on the ratio of their respective masses, and, just like the distances, the masses can also be quantified.

From the foregoing discussion we can identify a number of features of the Keplerian idea of mass. It has a static dimension, manifested by a body's tendency to rest. it has a dynamic dimension, expressed by a body's resistance to any motion applied from outside. This resistance depends on the quantity of matter (*copia materiae*). Finally, this (inertial) mass can be quantified. Obviously the Keplerian concept did capture several important elements of the classical concept of inertial mass. However, it fell short of the Newtonian in certain significant respects. For instance, Kepler still lacked the modern concept of inertia; he still remained very much under the Aristotelian influence. Furthermore, the resistance offered by the material body was to motion, not, as in Newton's second law, to acceleration. Despite these shortcomings, he did make a substantial contribution in the development of this concept of mass. Jammer was right when he observed that "the modern notion of mass had its inception in the seventeenth century conceptualization of inertial mass primarily by Kepler and Newton."[63]

THE DISCOVERY OF SCIENTIFIC LAWS

The scientific revolution was marked by outstanding discoveries of several laws of nature. In this respect too Kepler made remarkable contributions. His three laws of planetary motion were among the first true scientific laws in the modern sense. Not only did they help Newton in his later work, they also laid a solid foundation for modern astronomy. According to Mittelstrass, "with the formulation of the three laws of planetary motion not only 'substantial' astronomical propositions are changed, but also the axiomatic structure of astronomy itself."[64] This is so because earlier the principle of circularity and of uniform angular velocity constituted the axiomatic character of astronomy. Kepler's laws challenged the principle of circularity and called for a new set of axioms. As Mittelstrass once again points out, "whereas the 'Copernican revolution' took place within the traditional conceptual framework, it was the 'Keplerian revolution' which, by breaking with this conceptual framework, first effected a fundamental, namely a foundationally-determined change."[65]

Kepler's first law that the planetary path is not circular, but elliptical, was one of the most revolutionary discoveries in the history of astronomy because it broke with a tradition of about three thousand years. According to Hanson, rejection of geocentrism produced only a disturbance, whereas rejection of circularity effected a real revolution. "Copernicus himself thought it was a lesser evil to move the earth away from the center of the system than fail to fulfil the demand for uniform circular movement, that is the only 'natural' or 'physical' circular movement."[66] That is why Hanson could write: "The line between Ptolemy and Copernicus is unbroken. The line between Copernicus and Newton is discontinuous, welded only by the mighty innovations of Kepler."[67]

Someone may object to my claim that Kepler's revolution from circle to ellipse was more fundamental than the heliocentric revolution of Copernicus on the plea that what Kepler found was only a measure of quantitative detail. This objection would be valid if the issue were merely a matter of scientific accuracy. However, what was involved here was more a matter of scientific world view than of quantitative accuracy. The belief that only circular motion was possible for heavently bodies was well-entrenched in the religious, philosophical, and scientific traditions for thousands of years. We have no evidence that this was ever challenged by anyone, not even by a daring revolutionary like Galileo. On the other hand, geocentrism was seriously challenged by many, especially by Aristarchus already in the third century B.C., as admitted in the *De Revolutionibus*. Indeed, deviation from circular motion was noticed by astronomers, but as Copernicus himself declared, "Despite these irregularities, we must conclude that the motions of these bodies are ever circular and compounded of circles."[68] Tycho Brahe also had a similar view: "It is necessary that the orbits of planets be composed completely of circular motions, ... A rational mind would recoil with horror from such a supposition [of noncircularity]."[69] In fact, in one of his lectures, he stated that the hypothesis of irregular motion of planets is more absurd than the Copernican hypothesis.[70]

That Kepler's third law had a crucial influence on Newton has been persuasively argued by Hanson[71], Mittelstrass[72], and others. Hanson gives a fine demonstration of how close Kepler was to arriving at the correct law of gravitation.[73] Huygens developed the idea of centrifugal force, according to which the force F exerted on the thongs of a sling to keep a rock whirling was proportional to r/T^2. According to Kepler's third law, T^2 r^3. From these two results it follows that F $1/r^2$. It can be shown that from here to arrive at universal gravitation theoretically one needs only a short step, although the genius of Newton was needed to make the stride. "Imagine F to be exerted not on the thongs holding the rock in orbit, but on a hollow sphere of the thong's radius, within which the same rock describes the same orbit as before. Now the force the sphere must exert on the rock to keep it in orbit will also be of the form F $1/r^2$.[74] Let us now assume that this force is due to an attractive force operating between the sun of mass M and some planet with a mass m. Then F Mm/r^2. The introduction of a suitable constant leads us straight to the law of universal gravitation.

There is evidence that Kepler's third law had direct influence on Newton's discovery of the law of universal gravitation, claims to the contrary view notwithstanding . For instance, one of Newton's manuscripts reads: "I began to think of gravity extending to ye orb of the Moon, and (having found out how to estimate the force with which a globe revolving within a sphere presses the surface of the sphere), *from Kepler's rule... I deduced* that the forces which keep the planets in their orbs must be reciprocally as the squares of their distances from the centers about which they revolve...."[75] Kepler, indeed, must have been one of those giants on whose shoulders Newton could stand to view the new horizon of astronomy.

In recent times some Kepler scholars have questioned the scientific integrity of Kepler concerning some of the important data presented in the *Astronomia Nova,* more specifically the final table in chapter 53. Kepler refers to the distances involved in this table as the "most true distances from the sun,"[76] which were "found from absolutely infallible observations."[77] On the other hand, William Donahue argues that this table is "a fraud, a complete fabrication. It has nothing in common with the computations from which it was supposedly generated other than the mere dates and the data for the sun."[78] Indeed the table was "a later fabrication designed to justify the conclusions."[79]

All Kepler scholars admit that the table under consideration is highly controversial, but not all agree with Donahue's conclusion, despite his elegant reasoning and detailed analysis. Volker Bialas, for instance, although calls the section a "dark chapter in the *Astronomia Nova,*"[80] concludes that "Kepler did not deceive or manipulate values. He has put obscurely what would have required more explanation for a better understanding."[81] He bases his argument on Kepler's letter to Fabricius, written at about the same time as when this controversial chapter 53 was being composed, which talks about a new method of calculating the ephemerides. Bialas thinks that the data for the table came from this method, although Kepler has left the matter obscure and undeveloped.

It must be noted that the issue is not whether Kepler arrived at the law of the ellipse by fabrication, but rather whether he fabricated the distances to use them as evidence for his conclusion. It is well-established that Kepler could have arrived at the law by the method of "eccentric equations," and there is good evidence to show that this indeed was his path to the initial discovery.

Until this new method Bialas refers to has been identified and tested out, the controversy will persist and we either have to accept Donahue's fabrication thesis or go by Kepler's word. I am inclined to opt for the latter for a variety of reasons. All through his life Kepler remained a man of great integrity, even at the cost of substantial personal losses. Again, although later science considered the laws of planetary motion Kepler's most precious contribution, he himself did not share that view. It is hard to believe that Kepler would break his long-cherished principles to lend support to something he hardly considered central to his life-work. More importantly, David Fabricius, the Frisian clergyman and astronomer, was a persistent and informed critic of Kepler all through his work on Mars. He took Kepler to task on many counts, but not for fabrication of data. It was very unlikely that a "patent fraud," to use Donahue's words, would have escaped Fabricius. It is well documented that obscure style of writing and careless computation were nothing new to Kepler.

THE NEW METHOD OF SCIENCE

The development of the new science naturally involved a simultaneous development of a powerful method. Here too Kepler made a notable contribution. In this connection Mittelstrass's words are remarkable: "Kepler belongs to the founders of modern science. And he may be reckoned among them not merely because his achievements in the field of astronomy were a decisive precondition for Newton's achievements in the field of physics, but because his scientific work marks a *methodological* turning point in astronomy, through which, not only particular astronomical propositions, but also the axioms of astronomical methodology themselves were radically changed."[82] Even a brief discussion of Kepler's scientific method can lend strong support to this claim. Since Kepler never gave any systematic or detailed discussion of his method, we have to depend mainly on his actual practice and occasional statements on the subject.

Although many philosophers of science believe that no method can be regarded as the method of science, there is sufficient consensus that the Hypothetico-Deductive method is the most widely and effectively used scientific method. Often this method is closely associated with the names of Galileo and Newton. However, a close look at Kepler's work reveals that long before Galileo Kepler had developed this method in the course of his own scientific work. Unfortunately, he misled his readers by calling his method the "*a priori* method." In fact, one can show that it was essentially nothing but the H-D method.

Kepler's *a priori* method was a deductive method as opposed to the inductive, a *posteriori* method advocated by Tycho Brahe. This method begins by presupposing certain hypotheses for the explanation of natural phenomena. These hypotheses are expressed in mathematical formulations, and particular mathematical deductions are drawn from them. The mathematical formulations and deductions make the approach *a priori*, since they are considered strictly valid, unlike the merely empirical observations and generalizations involved in the inductive method. The propositions need not always be given a mathematical form although Kepler in his work usually did so.

The name *a priori* is misleading because, in its modern sense, it implies that observation has no real role in the method, which is far from the truth, because there is ample evidence that Kepler emphasized observation all through his scientific work. Already in 1595, in the prime of the *Mysterium Cosmographicum,* he wrote to Maestlin: "We can put all our hopes into it [the *a priori* method] if others cooperate who have observations at their disposal...."[83] To Herwart on July 12, 1600, he affirmed that the *a priori* speculations must not contradict manifest experience but rather agree with it."[84] Therefore the *a priori* method was not purely mathematical, and still less was it purely speculative, experience played a significant role, as was evident from Kepler's eagerness to consult Tycho's data to verfy his polyhedral theory.

Kepler insisted that the hypothesis should not be a product of some irrational or purely psychological process. He firmly adhered to the principle of rationality of nature and so according to him, a scientific hypothesis should have a rational basis. This was very clear from his response to Fabricius: "But you think that I can just invent some elegant hypothesis and pat myself on the back for embellishing it and then finally examine it with respect to observations. But you are far off."[85] A scientific hypothesis is not the figment of one's imagination, as he illustrated by a concrete example: "I demonstrated the oval figure from the observations..."[86] The same idea he expressed in another letter to Fabricius: "It is true that when a hypothesis is constructed from observations and then confirmed by them, I am wonderfully excited afterwards, if I can discover in it something consonant with nature."[87]

I have argued that in all his three major works (*Mysterium Cosmographicum, Astronomia Nova, and Harmonices Mundi*) the method used was the same.[88] I do not deny that there are some differences in the methodology of these three, but they are only a matter of degree of emphasis, rather than of basic nature. If we are inclined to believe that the *Astronomia Nova* is very scientific in method and the other two are unscientific, then perhaps we are prejudiced in favor of the theory that turned out to be correct. All his major works have basically the same method. The difference comes because of the differences in the objectives and corresponding domains envisaged by each: in the *Astronomia Novu* the goal is restricted since it confines itself to the motion of a single planet, the *Mysterium Cosmographicum* has a wider goal since it envisages the solar system, while the *Harmonices Mundi* has the widest goal because it empraces the whole cosmos. I suggest that the difference between the *Astronomia Nova* and the *Harmonices Mundi* is a difference between science of specific things (e.g., study of nuclear fusion reaction in the laboratory) and science of cosmic and general phenomena (e.g., study of the origin of the universe). They may differ in the accurate, reliable results they can provide but not in their basic methodology. Kepler used the H-D method in all his major works. He can be rightly considered the first among the moderns to use this method in science effectively.

Our discussion shows that Kepler's contribution to modern science was not confined to the three laws he is celebrated for. His role embraced every important aspect of science. Modern science is deeply indebted to geniuses like Johannes Kepler for making it what it is today.

References and Notes

1. Duncan *Mysterium Cosmographicum*, tr. A.M. (New York: Abaris Books, 1981), p. 225.
2. Uranus and other outer planets were discovered long after Kepler's time.
3. A numerical-relationship for the distances of the planets, proposed by Titius in 1772, later publicized by Bode. This relationship holds good for planets up to Uranus. it does not fit well for Neptune, but fits fairly well for Pluto.
4. *Gessammelte Werke*, ed. W. von Dyck, Max Caspar, F. Hammer, V. Bialas (Munich, 1937-) [hereafter GW], vol. VI, pp. 323: 1. 14-324: 1. 15.
5. However in a letter to Matthias Bernegger on June 30, 1625, Kepler reported that he had arrived at the moment of creations by calculation (see GW XVIII, nr. 1010: 11. 30-38).
6. Dreyer, J.L.E. *A History of Astronomy from Thales to Kepler* (New York: Dover Publications, 1953), p. 344.
7. Thomas Kuhn, *The Copernican Revolution* (Cambridge, Massachusetts: Harvard University Press, 1967), p. 135.
8. The geometrical center refers to the position or location of a body, whereas the dynamic center refers to a body's function or activity.
9. "Preface to De *Revolutionibus*" in *On the Revolutions*, ed. Jerzy Dobrazycki, tr. edward Rosen (Baltimore: Johns Hopkins University Press, 1978), p. 4. Emphasis added.
10. Kuhn, *Copernican Revolution*, p. 137.
11. Neugebauer, "On the Planetary Theory of Copernicus," in *Vistas in Astronomy* 10, ed. Arthur Beer (Oxford: Pergmon Press, 1968), p. 100.
12. Arthur Berry, a *Short History of Astronomy* (New York: Dover Publications, 1961), p. 123.
13. Quoted in Dreyer, *History of Astronomy*, p. 343.
14. Letter to Fabricius on August 1, 1607, GW XVI, nr. 438: 11. 41-43.
15. For instance, to prince Cesi, who criticized the presence of epicycles, Galileo wrote a firm reply on June 30, 1612: "We should not desire that Nature should adjust to that which seems to be best arranged and ordered, but we ought rather to adjust our intellect to her works, since they are certainly most perfect and admirable, and all other constructions would reveal themselves eventually as devoid of elegance, incongruous, and puerile..... If anyone wants to deny the epicycles, he must deny the else is the path of Mars according to the best observations?" (Georgio de Santillana, *The Crime of Galileo* [Chicago: The University of Chicago Press, 1961], p. 36).
16. Kepler's letter to Brengger on October 4, 1607, GW XVI, nr. 448: 11. 4-6.
17. For instance. consider Aristotle's explanation of projectile motion. The issue here was how a projectile like an arrow could continue to travel even in the absence of any external contact force. He tried to explain it by claiming a natural tendency for air and water to assist motion rather than resist it, despite

all contrary evidence from everyday observations.

18. I argue this point extensively in my book. *See The Discovery of Kepler's Laws: The Interaction of Science, Philosophy, and Religion* (Notre Dame: University of Notre Dame Press, 1994).

19. Max Caspar *Kepler* (New York: Dover Publications, 1993), p. 130.

20. GW VI, p. 226: 11. 21-22.

21. Kepler's letter to Fabricius on July 4, 1603, in GW XIV, nr. 262: 11. 129-130.

22. GW III, p. 191: 1. 11.

23. Kepler's letter to Fabricius on October 1, 1602, in GW XIV, nr. 226: 11. 394-395.

24. Owen Gingerich, "Kepler, Johannes," *Dictionary of Scientific Biography,* vol. 7 (New York: Charles Scribner's, 1973), p. 292.

25. Letter written on February 28, 1624, in GW XVIII, nr. 974: 11. 211-213, tr. Carola Baumgardt.

26. GW XVII, nr. 744: 11. 24-30.

27. Written on February 10, 1605, in GW XV, nr. 325: 11. 57-31, tr. Koestler.

28. Johannes Kepler, *Joannis Kepleri astronomi opera omnia,* ed. Christian Frisch, vol. VIII (Frankfurt and Erlangen, 1857-71), p. 148. Quoted by E.A. Burtt, Metaphysical Foundations, p. 68.

29. Written on April 9, 1597, in GW XIII, nr. 64: 11. 10-16.

30. Simplicius' *Commentary* reads: "Plato lays down the principle that the heavenly bodies motion is circular, uniform, and constantly regular. Thereupon he sets the mathematicians [i.e., astronomers] the following problem: What circular motions, uniform and perfectly regular, are to be admitted as hypotheses so that it might be possible to save the appearances presented by the planets?" (Pierre Duhem, *To Save the Phenomena,* tr. Edmund Doland and Chaninah Maschler [Chicago: University of Chicago Press, 1969], p. 5).

31. Quoted in Jardin, *Birth of History and Philosophy of Science* (Cambridge: Cambridge University Press, 1984), pp. 144-145.

32. Ibid., p. 145.

33. Alexandre Koyr, *The Astronomical Revolution* (Ithaca, New York: Cornell University Press, 1973), p. 419, #6.

34. Idem.

35. See Jammer, *Concepts of Force* (New York: Harper torchbooks, 1962), p. 90.

36. Koestler, "Kepler, Johannes," *The Encyclopedia of Philosophy,* vol. 4 (New York: Macmillan, 1972), p. 333.

37. Jammer, *Concepts of Force,* p. 81.

38. The center of the earth (which for him was the center of the universe) was a uniquely privileged place, being the natural place for all earthy bodies. Since all bodies had a natural tendency to move to their natural places, all earthy bodies moved to the center of the earth. The Aristotelian idea of gravitation basically involved this phenomenon.

39. GW XV, no. 340: 11. 140-144.

40. See GW III, p. 25: 18-26: 3.

41. *Kepler's Dream*, by John Lear, tr. Patricia Kirkwood (Brekeley: University of California Press, 1965), p. 151.

42. Jammer, *Concepts of Force*, p. 84.

43. Kepler's letter to Brengger on November 30, 1607, in GW XVI, nr. 463: 11, 34.

44. *New Astronomy*, tr. William Donahue (Cambridge: Cambridge University Press, 1992), p. 55.

45. William Gilbert, *De Magnete* (London: Petrus Short, 1600), p. 217, quoted by Jammer, *Concepts of Force*, p. 86.

46. GW III, p. 242: 11. 29-30.

47. See ibid., p. 244: 11. 12-13.

48. See ibid., p. 243: 11. 30-31.

49. *Tertius interveniens*, GW IV, p. 192.

50. GW III, p. 241: 11. 10-13. See also Jammer, *Concepts of Force*, p. 87.

51. Tr. A.M. Duncan (New York: Abaris Books, 1981), p. 203.

52. Jammer, *Concepts of Force* p. 91.

53. Mittelstrass, "Methodological Elements of Keplerian Astronomy," tr. J. Fearns, *Studies in History and Philosophy of Science* 3 (1972), 203-232.

54. Jammer, *Concepts of Mass* (Cambridge, Massachusetts: Harvard University Press, 1961), p. 52.

55. *Kepleri Opera Omnia*, vol. 7, p. 746.

56. Ibid., vol. 2.

57. Ibid., vol. 1, p. 590, tr. Jammer.

58. GW VII, p. 296: 11. 31-33, tr. Jammer.

59. Literally the last part of the quotation reads as follows: "with respect to the motive force, the inertia of matter is not like nothing to something." (GW VII, pp. 296: 1. 42-297: I. 2). For the translation, see Jammer *Concepts of Mass*, p. 55.

60. GW VII, p. 301: 11. 22-25.

61. P. 171.

62. GW III, p. 25: 11. 32-36.

63. Jammer, *Concepts of Mass*, p. 3.

64. Mittelstrass, "Methodological Elements," p. 207.

65. Idem.

66. Fritz Krafft. "The New Celestial Physics of Johannes Kepler," in *Physics, Cosmology and Astronomy, 1300-1700: Tension and Accommodation*, ed. Sabetai Unguru (Dordrecht: Kluwer Academic Publishers, !991), pp. 191-192.

67. Hanson, "The Copernican Disturbance and the Keplerian Revolution," *Journal of the History of Ideas* 22 (1961), p. 169.

68. Tr. *Copernican Revolution*, p. 147.

69. Letter of Brahe to Kepler written on December 9, 1599, in GW XIV, nr. 145: 11. 206-207 & 1. 205.

70. See Kristian Moesgaard, "Copernican Influence on Tycho Brahe," in *The Reception of Copernicus's Heliocentric Theory*, ed. Jerzy Dorzycki (Dordrecht: Reidel, 1972), p. 32.

71. Hanson, "Copernican Disturbance," p. 183.

72. Mittelstrass, "Methodological Elements," p. 211.

73. Hanson, "Copernican Disturbance," p. 183.

74. Idem.

75. Additional manuscripts of Sir Isaac Newton, MS 3968, nor. 41, bundle 2, in the Cambridge University Library. Quoted by Hanson, "Copernican Disturbance," p. 183, emphasis added.

76. GW III, p. 337: 1. 27.

77. Ibid., p. 344: 1. 27.

78. Donahue, "Kepler's Fabricated Figures: Covering up the Mess in the *New Astronomy*," *Journal for the History of Astronomy* 19 (1988), p. 233.

79. Ibid., p. 232.

80. Bialas, "Keplers Komplizierter Weg sur Wahrheit: Von neuen Schwierigkeiten, die '*Astronomia Nova*' zu lessen" in Berichte zur Wissenschaftsgeschichte 13 (1990), 171.

81. Ibid., p. 174.

82. Mittelstrass, "Methodological Elements," p. 205.

83. Kepler's letter to Maestlin on October 3, 1595, in GW XIII, nr. 23: 11. 204-205, tr. Baumgardt.

84. See GW XIV, nr. 168: 11. 108-109.

85. Kepler's letter to Fabricius on July 4, 1603, in GW XIV, nr. 262: 11. 127-129.

86. Ibid., nr. 262: 11. 158-159.

87. Letter to Fabricius on July 4, 1603, in GW XIV, nr. 262: 11. 129-131.

88. See my book *The Discovery of Kepler's Laws*, pp. 108-109.