13 Johannes Kepler (1574-1630) and the Revolution in Astronomy

Kepler was arguably the greatest Natural Philosopher of his generation and probably one of the two or three greatest ever--probably ranking with Newton or Einstein. He worked in all the traditional, developed fields of science -- in mathematics, optics, geometry, as well as in astronomy . (Even in astrology, which was a science of course, that he wanted to revise and make more accurate.) He made revolutionary or major advances in all of those areas. For example, in optics our modern theory of how the eye works, that it is a device for focusing inverted images on the retina, was first put forward by Kepler.

Kepler is a difficult figure to deal with because of his basic background beliefs, which in this case take the form of his background Natural Philosophy through which he pursued his researches of the various sciences. Kepler was neither an Aristotelian nor was he a member of that school which was going to come to dominate, after his death, the so-called mechanistic school of Natural Philosophy. Kepler falls into a third group of Natural Philosophers influenced and devoted to Platonic and neo-Platonic ideas. But whereas Copernicus was a bit of a luke-warm semi-Platonist, still very much an Aristotelian in many ways, Kepler was a very dyed-in-the-wool, Renaissance Platonic Natural Philosopher. This meant he believed certain things that we must now establish.

1. Kepler’s Natural Philosophy -- the Metaphysics of his Astronomy:

First of all, Kepler believed that there was a very simple, elegant, very beautiful mathematical blue-print for the structure of nature. He believed that God had designed that blue-print and God had, of course created the world in an attempt to materialise that blue-print. ('blue-print' is not Kepler’s terminology -- he would have said ‘mathematical relations or harmonies’)

No blue-print is absolutely perfect in its execution, but the traces are there if you look closely. That leads us to the next point: Kepler believed mankind could uncover this mathematical blue-print. Man can know these relationships or harmonies (of the blue-print) for man is endowed with a very capable mind, intelligence and soul. Platonism was always very optimistic about the human mind’s capacity to plumb the deepest secrets of the divine mathematical blueprint. The final point is, that when in the course of empirical researches simple elegant mathematical relationships emerge, then you know you have discovered part of the truth, part of the blue-print. Simple mathematical relationships are apparently found in nature are self-validating. What do you expect your research to turn up: complications, confusions? -- well if it does, you are not getting the truth. **When simple regularities show up in the data those are the true laws of nature as decreed in God’s blue-print.**

Now, Kepler was a Natural Philosopher as well as a professional astronomer and that means compared to Copernicus he had a much more serious concern with, for example, explaining the causes of motion and changes. He was a ‘real’ Natural Philosopher, like Aristotle, not a more limited professional astronomer, like Copernicus. And Kepler was interested in explaining the causes of motion and change as any good Natural Philosopher would be. But here again, he is not an Aristotelian --he does not tell us about bodies pursuing their inward programmed natural motions. Nor is he of the coming mechanist school -- he does not tell us about the collisions and interactions of atoms and microscopic particles. Kepler tells us about something else which is very Platonic. He tells us about the existence in the world -in nature --of various sorts of forces or powers which are not material in character. They are immaterial--if you like--they are spiritual.

These forces or powers cause certain phenomena to happen or certain motions to occur. These powers or forces act according to laws which can be expressed in simple mathematical terms, laws which govern the behaviour of these powers. An example of an immaterial power, for Kepler, was light, which is not matter. Light comes from the stars, it gives life--it is not material, it is a spiritual thing. Light travels at an instantaneous speed--which mere matter cannot do. Light obeys mathematical laws. Kepler was the first to write this law: the intensity of light coming from a point source varies inversely at the square of the distance away from that source. For example, a point source of light gives out one unit of illumination at a distance of one unit, then at double the distance from the source you get a quarter the illumination; at triple the distance a ninth of the illumination. This is a harmony and there are other harmonies of light. For example: the angle of incidence equals the angle of reflection. He couldn't quite work out the law of refraction but he tried.

So the picture we get from Kepler is a kind of Platonic hierarchical view of reality. At the top is God and at the bottom is 'brute matter'. In between are things of intermediate value. Human souls are very high value and capable of understanding the divine blue-print. Human souls have free-will, they have intelligence, therefore, they are high-level spiritual things. A little bit lower are powers and forces --which are spiritual, not material--but they do not possess free-will. Light does not possess free-will although it possesses spiritual power. Light follows the laws--the laws are the elegant, mathematical decrees of God.

There were other immaterial forces apart from light. There was, for example, magnetism (a very hot topic in the 16th century) what with the use of the compass in navigation; many practical and navigational books written about magnetism and William Gilbert's book, *On the Magnet* of 1600 which was very important in Kepler's thinking. Magnetism clearly is an immaterial force acting upon matter. Kepler could not figure out what the law was though--for it's a tough one--but he thought there was one. And, there was another immaterial force which comes from the sun, just a the light does : the planet moving force. -We are going to hear more about this below. Obviously Kepler is going to look for the law of this particular force--but not from an Aristotelian and Mechanist standpoint. As a Copernican working after Tycho shattered the crystalline heavenly spheres, Kepler needed a cause to move the planets, and in Kepler's case, a mathematically describable special immaterial force emanating from the sun.

I do not think I need to tell you that we should not laugh at Kepler or his metaphysics. We know that interesting science can be done under various Natural Philosophies, under various metaphysics, and Kepler did absolutely pivotal work in astronomy and optics at a crucial turning point in the history of those sciences, and yet he had a Natural Philosophy which very quickly after his death was going to be thought by leading thinkers in the 17th century to have been nonsensical, and even dangerous, because they were almost all mechanists.

We get echoes of this in Whiggish histories of science which assume that the mechanical philosophy was the only good or correct metaphysical background in which to pursue science; the only progressive metaphysics. This misses the point that in different times and different places important science has been done under contrasting types of metaphysical assumptions. Kepler is a good example--here he is amongst all these Aristotelians, soon to be mechanists, and he is a raving Platonist and yet a crucial figure.

2. Kepler's Revolutionary Approach to Astronomy:

One way to deal with Kepler's career is to orientate ourselves by bearing in mind the title of an article which an historian of science wrote about 35 years ago called 'The Copernican Disturbance and the Keplerian Revolution'. Consider Copernicus' system, that is, the one that Copernicus set up himself, (for you must remember that in this story Kepler called himself a Copernican, although his theory is quite different from Copernicus'). Newton and many others will also do the same-- change and reinterpret the theory whilst calling themselves 'Copernicans'. As for Copernicus' own Copernicanism, perhaps you can argue that it was revolutionary as a whole (although I am not so sure), but it is pretty certain that all the 'parts' of which it was made were traditional. You have uniform circular motion, epicycles and deferents; the centre of the system is not really the sun, it is the centre of the earth's orbit; you have a lack of concern for the physical paths of the planets in space (and this was a typical attitude since the Greeks). Everybody knows in some sense they are cycling around, and even in Copernicus they do this for he has little epicycles to account for this. Nobody is very worried about the little loops they do in space--it is done to get the predictions as accurate as possible, given the available data.

Now if you look at Kepler you see he has different concerns, which are really modern concerns (which are still with us). First of all, the sun is the physical and dynamical centre of this system. In some sense this is still true. We today do not use Kepler's theory of this, but we accept this as broadly true in Newtonian or Einsteinian terms. Kepler is concerned with what causes the motions of the planets, for he is not happy to say "they are doing what comes naturally". Kepler has a whole new way of attacking that problem of the physical causes of the motions of the planets. He is concerned with the shape of the orbits in space. He does not like the idea that they would trace out loops. Kepler wanted a "God's eye-view" of those orbits and expected them to look simple and elegant when you take such a view. Of course, what he finds is that they cannot be circles, but he also finds that they do not have to be combinations of circles either, for they can be nice, pretty ellipses. Parts of his system are absolutely novel in contrast the whole Greek and Medieval astronomical tradition, including Copernicus and Tycho. So he may be a follower of Copernicus and he may call his theory the 'Copernican Theory' but one begins to wonder whether Kepler is not trying to pull off a rather genuine theoretical revolution in astronomy where Copernicus was a bit hesitant, ambivalent and confused.

Kepler even invented a new science--a new field of research--that encapsulated his concerns. We still have this science. In fact in the hands of Newton, this science became the central physical science, the one that all the rest of them tried to model themselves on. This science is celestial mechanics which means: the study of the mathematical laws of the physical causes of the motions of the planets. What are the mathematical laws of the forces that produce the elliptical orbits of the planets about the sun? Nobody had done this before--in a way what Kepler is doing with the celestial mechanics and all his metaphysical concerns with mathematical blue-prints and immaterial forces, is saying,

> I am going to bite the bullet about Copernicanism. I am going to supply you with a physical explanation at least of how the earth and planets can move and my physical explanation is also going to produce the astronomical details.

In other words astronomy and Natural Philosophy are going to become the same--isomorphic. Ptolemy and Aristotle never quite pulled that off--for there was always a gap between the physical explanation and what you had to do in astronomy, where much of the necessary 'apparatus' of theory was physically implausible. That's why Kepler is so important. But note, his Natural Philosophy, the key to his approach, was an unusual and minority view- a peculiar brand of neo-Platonism.

3. Kepler's Program & Early Work: <u>The Mysterium Cosmographicum</u> (1597)

Most of Kepler's aims were present in his earliest works. Later in this Chapter we will talk about his more famous work on planetary motion, which managed to survive and be re-interpreted by Newton to become part of modern science. Some of his early work seems bizarre (from our standpoint), but from his standpoint was completely consistent with and at the centre of everything he tried to do, including his later work. In fact, it was in his view much more profound and more important than anything he did later.

This early work is encapsulated in his book the *Mysterium Cosmographicum* (which means the cosmological mystery and what he should really have called it was 'How I solved the cosmological mystery' because that is what he claims--for he thinks he has discovered the essential components of the blue-print). This was written whilst he was in his twenties and a mathematics teacher in a town in one of the provinces of the Austrian Hapsburg Empire. When he got kicked out of there because he was a Protestant ,he remained in the Hapsburg Empire but he went and got a job in Prague with Tycho Brahe--which proves that the higher level institutions were still a bit more tolerant, whereas local provincial institutions weren't. In this book he exposes himself as that rarest of 16th century creatures, a genuine believer in the truth of Copernicanism. People like that you could count on two hands in the late sixteenth century.

Kepler's point in the *Mysterium Cosmographicum* can be put this way: According to Copernicus the compelling reason to believe his theory was the existence of the cosmic harmonies of structure. But Tycho had harmonies also and claimed to have a better theory on other criteria. Kepler, as a Copernican, saw very brilliantly that what you had to do in this situation was to find more harmonies to out-harmony Tycho! For if Tycho has stolen all the harmonies you initially possessed, you had better find some more in the Copernican system, hoping that they would not be there in the Tychonic system, for obviously this battle is going to be settled on by counting harmonies, more or less.

But, it was not just a question really of 'more' harmonies, for some harmonies are more deep and profound than others. Some harmonies condition whole sets of harmonies and if you could find these really deep ones then you would really be getting somewhere. So what Kepler focuses in on is the following sort of problem involving deep, structural harmonies:

You have three systems: if Tycho or Ptolemy is right there are seven objects going around the earth--the moon, sun, and five planets. So the blue-print must contain some rationale for there being seven things going around the earth. But, if Copernicus is right, there are six things going around the sun. (Why the earth has a moon is a bit of a problem for the Copernicans but anyway there are mercury, venus, earth, mars, jupiter and saturn - the six planets.) Now what if Kepler could find the blue-print that explained: (a) why there had to be six and only six planets, and moreover, (b) what if you could also find the blue-print for the relative distance of these six objects from the sun, for remember Copernicanism gives you these relative distances which Ptolemy does not. This would clinch the whole case in Kepler's favour.

In order to understand the *Mysterium* , you have to be reminded of two geometrical concepts: the concept of inscribing a circle in a plane figure and circumscribing a circle around a plane figure. (fig. 1) When you inscribe a circle in a regular plane figure, it means that the circle touches the figure in the middle of each side and only at those points. There is only one circle that can be geometrically so inscribed in a given plane figure. Now to circumscribe is the same sort of idea--the circle must touch the figure at the corners, at its vertices, only. You can play this game with three-dimensional solids as long as you are using what is called 'regular' solid -- the symmetrical solids that have the same plane-figure of each of their faces. (fig. 2) Now the "perfect solids" are: (1) the tetrahedron (pyramid) bounded by four equilateral triangles; (2) the cube (six squares); (3) the octahedron (eight equilateral triangles); (4) the dodecahedron (twelve pentagons) and (5) the icosahedron (twenty equilateral triangles). There are only five such symmetrical solids, there are no other such regular solids in 3-dimensional space. Euclid proved it and every mathematician and Platonist afterward knew that. There is something mysterious and tantalising about that fact--why? Kepler did not know why, but he was impressed by the fact that there were five and only five perfect solids.

Kepler starts playing around with the idea that you can circumscribe a sphere around one of these solids, and inscribe a sphere inside one of these solids--just as we circumscribed a circle around a regular plane figure, and inscribed a circle within a regular plane figure. But, hold on, there are only five regular solids, which means that if you start at the outside with a sphere, and then you put in a solid, and then you put a sphere inside that, and then a solid inside that sphere, and then a sphere inside that solid, and you do that with the five solids, you wind up with six spheres. Fives solids can determine the number and the sizes of six spheres, by mutual inscription and circumscription. And, there are six planets and only five perfect solids!

Kepler played with this idea, trying to fit such a pattern of 6 spheres and the 5 perfect solids, for years and years, doing an awful lot of mind boggling solid geometry, finding which one should be placed where, in order that the circumscribed and inscribed spheres should mimic the relative distances of the planets from the sun--relative distances determinable by means of Copernicus' theory (one of the harmonies indicated in Chapter 8). The answer was yes, you can produce a solution, if you are Kepler, and the accuracy of the fit is 95%, that is, given the data he had on relative orbital sizes his model had roughly a 5% error factor. (fig. 3)

So let's make this clear: Kepler thinks he has the reason why God created only five perfect solids; it's because He was going to create only 6 planets, and He was going to lay down the blue print by spacing out the distances of the orbits, using this technique of inscribing and circumscribing spheres (containing the orbits) nested within the series of five perfect solids.

Do not think that Kepler thought these spheres or solids were up in the heavens, this is the blueprint; there is nothing to prevent the blueprint being a 3-dimensional model, as in figure 3. This is something like the blue print God used when he decided to make 6 (and only 6) planets and to put them at specific relative distances from the sun; the objects in the diagram are not in the heavens--only the six planets and their variously sized orbits are there--this stuff is on paper in Kepler's study--and stuff like that was in God's mind...and now they are in Kepler's mind! When very simple and elegant results come out of your researches, Kepler believes that you have found the truth -- the blueprint. 5% error is good enough -- after all he's got 100% accuracy on the number of planets! And 95% accurate on the distances--this, then, is the Divine blueprint, and God obviously is a Copernican! (Until, of course, somebody finds another planet--but that will not happen for another 180 years--not a bad run.)

Kepler's model was dismissed a long time before that--but that was only because Natural Philosophies changed, the dominant metaphysics of the sciences changed. Within Kepler's metaphysical framework this seems a dazzling, crucial research result--the Cosmographical Mystery indeed--a deeper harmony, a more profound piece of the blueprint, than even Copernicus had got in his work, and, Tycho can't match this -- so Tycho's wrong.

There was only one problem from Kepler's standpoint--it only fits to 95%. Tycho has got really accurate data--it would be nice to see how this stacks up against the best available data, for Kepler had very high empirical standards, just like Brahe. He wasn't just a Platonic Natural Philosopher. It was clear to him, and this is maybe where his Protestantism comes in, it is not enough just to think it out, you really have to do the hard work, with the best data, to really show this is the way things are. He was not going to let this ride, he was going to try to find out whether the better data seriously upsets or confirms this picture. And that, along with the fact that he lost his teaching job led him to being on Tycho's doorstep in 1600 to apply for a job as an assistant.

I will not be tracing the story of Kepler's later work on this arrangement. You may wonder though did he evergive it up? No... There was nothing in Tycho's data to upset it--the data did not make it any better than 5%...but it was still sufficiently accurate, and he continued to believe this and worked within it for the rest of his life.

His attention was diverted into the direction of the problem of the shapes of the orbits and the causes of the shapes of the orbits and the motions of the planets on those orbits. His work on these matters lived on to be reworked by Newton and to become central parts of our later scientific canon. We shall discuss these in a moment

What's interesting here is that we have an astronomer and Natural Philosopher, some of whose work is still part of the scientific canon, but here is a part of his work that he was perhaps even more proud of, because to him it was more fundamental, and it comes out the same metaphysical background from which his more well known, long-lived results emerged. And yet that work to us is a fossil: It would have looked very exciting to certain people at a certain point of time, and within a certain metaphysical framework, but we have no trouble being completely unserious about. The same metaphysics and the same scrupulousness produced all these results, the ones we think are absurd, and the ones still in the text books. Kepler was working within his own Natural Philosophical and metaphysical background and he produced that to us bizarre insight, but to him crucial insight that God's blueprint really had been the Copernican one, because there exist only 5 perfect solids and 5 perfect solids space out 6 planetary orbits only.

4. Toward the Laws of Planetary Motion:

Now we will look at work that grows from the same Natural Philosophical and metaphysical background, but had a greater survival value, and so this comes down as the fundamental laws of planetary motion, but, note this well, it comes from the same way of thinking as that which led to the *Mysterium Cosmographicum.*

When, in 1600, Kepler was kicked out of his teaching job, he managed to secure a position as an assistant to Tycho Brahe in Prague. As Kepler was a serious astronomer, he was one of the major assistants, there were lower level workers there too. Kepler was given the job of working on one of the planetary orbits, that of Mars. He job was to try to work out the orbit of Mars, in some detail, according to the Tychonic system. But of course that wasn't what Kepler was interested in, for he was interested in the orbit of Mars in the Copernican system. Fortunately or unfortunately, Tycho died the next year and Kepler, after some struggle with Tycho's family, was able to get access to Tycho's data, which was considered family/private property. Kepler needed the data to work on the 6 sphere, 5 solid model, and to work on the orbit of Mars.

Mars' orbit is the second most eccentric, the second least circular (Mercury has the most eccentric orbit, but it is difficult to observe because it is near the sun and has lot of gravitational perturbation.)

Over 8 years of work led Kepler to develop his first two fundamental principles or laws governing planetary motion in the Copernican system; published as the *New Astronomy, or Celestial Physics* in 1609. These results were genuinely revolutionary, but they only gained their ultimate importance 80 years later via Newtons' use, and re-interpretation of the laws at the basis of his own system of physics and astronomy.

Let's look at how in fact these laws were developed. Our analysis of their 'discovery'--or was it their 'construction-has much to say about scientific innovation in general.

Here is the so-called first law of planetary motion: (fig. 4) Each planet moves in an orbit, which is an ellipse. An ellipse is a curve defined by two points, called foci, and by the fact that, for any point on the curve (x) , the sum of its distances from the two foci is a constant quantity. Kepler states that each planet's orbit is an ellipse--and the sun is at one focus of the ellipse.

Here is his second law of planetary motion: (fig. 5) Imagine a Planet going around in its elliptical orbit and imagine a line connecting the sun to the planet. The law states that in any two equal intervals of time, the line sweeps out equal areas. This law in effect controls the motion and speed of the planet. Very qualitatively speaking, the closer you are to the sun, the faster you move--the further away you are the slower you move.

The first law governs the shape of the orbit and the location of the sun. The second law governs the speed of the planet from instant to instant as it traverses that ellipse, and if you think about it, the speed of that planet is changing from moment to moment.

So, with the two laws we have the shape of the orbit in space, and speed along the orbit in space. A God's eye view--not a Ptolemaic or Copernican theoretical model for generating angular position only. It is meant as a true representation of the shape of the orbit in space and of the real (shifting) velocity of the planet over time--a representation that is simple and elegant, hence in Platonic metaphysical perspective, true.

These laws certainly are odd and strange. To those of us who have studied Newton's physics, they are less strange, because they form part of the groundwork for Newton's theory, but they were invented before Newton was born, from a background not of Newtonian physics, and in a period when ancient and Medieval ideas still pertained in astronomy, even in Copernicus and even in Tycho.

In 1609 these laws were bizarre. Why ellipses? Why the sun at one focus? They seem mystical. The areas law is even more peculiar and counter-intuitive. How does this happen? How do planets obey such a strange rule of motion?

This, then, is Kepler's version of Copernicanism. It does not bear much resemblance to Copernicus' version of Copernicanism. In fact it is unlike anything in the tradition of theoretical astronomy going back through to Ptolemy and back to the school of Plato. This is because the (combinations of) circles have disappeared, *replaced by what purports to be a physically true representation of the shape and dynamics of orbital motion*. Nor does this bear much relation to Newton's version of Copernicanism to come--although some Whig historians of science have always seen Kepler's work as just a step away from that of Newton.

Now the big question. How did he get these laws? Notice I avoid the term 'discover'. Laws of nature are not there to be discovered--they are 'constructed' and imposed'--just like the theories we have been studying. We do not have the time to trace these pathways of 'construction' in detail, but we shall canvass some pertinent hints and glimpses of how the job was done.

We could, of course, have a naive inductivist method story, based on the old story of scientific method and myth of facts. For law #1 at least the story could go like this: Kepler says I am going to find the orbit of Mars, using cardboard and pins, drawing the sun in a particular position, putting angles in and then putting pins in whereever there has been an observation of Mars. He does this for 8 years, then says, 'Ah! I can draw a curve through these points...It's an oval...no, its an ellipse--found by induction--generalisation of 'facts'.

In fact he did not do it that way. In principle you can't do it that way. Having angular measures of the positions of the planet in the sky does not give you sun-planet distances--to get those you have to make assumptions to build up an orbit; assumptions about speeds for example.

Here is a hint about how he found the first law: The second law was first, and first law was second, and, the second law (which was first) was not discovered, it was stated--stipulated in view of his metaphysical commitments and aims. From the second law (which was first) as a stipulation, he stumbled and bumbled his way to the first law (which was second). So, the second law is an excrescence of his metaphysics and the first law follows in step, on its basis.

Let's flesh this out a bit by returning to 1597, to the *Mysterium Cosmographicum* and to a point made previously, that Kepler was not only interested in deep harmonies but he was, as a Platonist, interested in the understanding of these spiritual/immaterial forces that cause motions and phenomena in nature. In 1597 Kepler believed in some sort of planet moving force keyed to the sun, because he knew or suspected the following:

> (1) that the sun must do more in the Copernican system than just sit in the middle and light up the system, as in Copernicus' own theory. Something must move the planets and presumably the sun had to do with that-- that's why it is 'central'.
>
> (2) a couple of "facts' seemed to fit in with that suspicion. (a) Kepler had found that the planes of the orbits of the planets intersect in the sun. This implied that the orbits are controlled by the sun. (b) The closer to the sun a planet is, the faster it moves, further from the sun, the slower it moves. (This result comes from Copernicus' harmonies-- you can get the relative distances of the planets from the sun, and you can get their periods of revolution around the sun--further out a planet it, the longer its period--slower it goes around the sun.)

If you are Kepler and you put this together these facts and your own metaphysics you get a speculative idea--the sun gives off a force that moves the planets. This force decreases in strength with distance. The force provides the motion/speed of the planet, so the more distant you are the slower you go. From that mix he speculates that this force is emitted from the sun, not by its entire spherical surface, but only near the plane of the orbits of the planets--more or less in a dish shape, off the sun's equator (fig. 6). He had that idea in 1597 because of that mix of metaphysical suspicions and facts that he had at that time. That in itself is a very weird idea but you can see it is very consistent with his pattern of thoughts.

Now let's go on to the work after 1601 on the orbit of Mars. He has to find out the shape of the orbit. To find this out he must make assumptions about how the planet moves, in order to work on the theory of the orbital shape. The assumption he makes is that the sun moves the planet Mars according to his speculative law of planet moving force weakening with distance.

But there is a problem--it is difficult to work mathematically with this law that force (and speed) vary inversely with distance from the sun. So he makes up a mathematically simpler, more useable approximation to it. You guessed it, *this pragmatic simplification of the force law idea is the law of areas.* Kepler uses the area law, which is just barely mathematically workable, if you don't have calculus and are willing to put in a lot of time calculating and breaking things up into very tiny sectors, for practical purposes of calculating. But in strict mathematical terms it is not a rigorously acceptable approximation of the first idea--yet he uses it. The areas law in mathematical terms is illegitimate simplification--Kepler knew that but he was a physical scientist, not just a mathematician.

So the Second Law is a stipulation--a mathematical simplification of the first idea of the planet moving force, itself a metaphysically conditioned construct related to other theory-laden 'facts'. He didn't 'discover' any fact of nature here. He had to make decisions about concepts which depended upon his metaphysics, his earlier metaphysically shaped 'facts' about the sun, and based upon the direction and aims of his course of research. That is how the second law was intellectually constructed and put to work.

Now, given the second law and Tycho's data--both are necessary--you can get the first law. He did bumble and stumble -made errors, some of which fortunately cancelled themselves out. Whig history concentrates on this story -- but the analysis should start with how and why he got the second law--which is not a discovery--but an expression of his metaphysics and his metaphysics loaded facts and research aims. The first law was then equally a construct, an artefact, not a discovery of raw fact in nature. (fig. 7 schematises this long path of research and construction)

In the *New Astronomy* Kepler sets out these laws with incredible detail of how he found them. He also explains the laws, articulates his ideas on the planet moving force. This is what his new science of celestial mechanics amounts to: the two new revolutionary laws in their full mathematical form and their explanation by means of a theory of celestial force--the planet moving force!

How does Kepler explain the laws--He engages in some more metaphysically conditioned physical theorising: The sun gives off light in all directions. It gives off the planet moving force in the plane of the orbits of the planets, around the equator, middle of the sun. It comes out in the form of spiritual rays, or rays of force, as light does, but only in the plane of the orbits of the planets.

So we have the planet moving rays like light rays--immaterial--causing or carrying a force. How do they move the planets? Well let's assume the sun rotates on its axis, so these spiritual rays, spiritual spokes emanating from the equator of the sun spin with it like a fan or propeller. If a planet is out there in the vortex, the force rays will pass through it imparting it motion. So the sun creates this spiritual windmill effect, the spokes spin through. The closer you are, the more spokes per minute pass through you, so that you move faster. (fig. 8)

Wasn't Kepler pleased in 1611 when Galileo observed sun spots with the telescope and concluded that the sun spins on its axis--this 'confirmed' Kepler's theoretical 'prediction' that the sun must rotate on its axis!

However, all this physical theory will not give you an ellipse--this is just an explanation of what pushes the planet around. What determines the ellipse, which comes close to and then passes farther away from the sun?

Clearly if you are Kepler, you need another force, to push and pull the planet close to/away from the sun. There is one force to sweep the planet around the sun and there is another force to move it in close and away from the sun. So two forces--the sun's planet moving force gives the rotation, another one will give the push pull. (Newton later will only need one force--gravity--here's a hint Kepler needs two forces because he has no conception of (Newtonian) inertia in his system.)

Where does Kepler get the idea for the second force? Well in 1600 William Gilbert, Queen Elizabeth I's physician had published a book called *On the Magnet*. He concluded for the first time that the earth is a big magnet with a north and south magnetic pole. Gilbert is a bit of a Platonist as well -- magnetism is a special immaterial force. All the planets might be magnets he speculated, and that might explain their motions.

Kepler is happy to see earth as a magnet and magnetism as an immaterial force. He elaborates this theory for his own purposes. The sun he argues also is a magnet, but a weird, special kind of one--its south pole is buried deep within it, its north pole is spread all over its surface. So the sun is effectively a north pole only. (Theories can make you say funny things, if you need to). The Earth is a big magnet with a north and south magnetic pole, respectively close to the geographical north and south poles.

That means the earth's magnetic axis is permanently tilted with respect to the plane of the earth's orbit--just as its axis of rotation is permanently tilted about 23 degrees with respect to that plane. This then means (fig. 9) that we can get the earth moving now closer to, now further away from the sun: In the Northern summer, when the earth's axis is tilted toward the sun so that the northern magnetic pole is closer to the sun than the southern magnetic pole, there will be a net repulsion from the (northerly) surface of the sun. Consequently the earth will drift away from the sun as it orbits. But by the time we reach the Northern winter, the southern magnet pole is closer to the magnetic 'northern' sun, and a net attraction will be exerted to pull the earth back in as it continues to orbit.

That is Keplerian celestial mechanics -- very odd, very different, and not really particularly Newtonian.

5. The Reception of Kepler's Theories: Dissolution and Flexible Interpretation

The question to ask about any great figure is: How his work was received? Work in science is only important, and indeed only has meaning in terms of what subsequent figures do with it, or to it. We have already seen the strange career of Copernicus' actual claims in the hands of his various friends and enemies. The differential reception and interpretation of Kepler's body of work is a wonderful case of how real scientific behaviour contradicts what a simple or Whiggish view would expect.

Take a figure like Galileo, a contemporary of Kepler and one of the few other convinced Copernicans. Does he embrace this work and integrate it with his own? Not at all. He largely ignores Kepler. It is as though he is embarrassed by the extreme neo-Platonism and harmony-mongering of his 'ally'. In addition he does not seem to have understood, or have wanted to understand Kepler's astronomy of non-circular motions.

What did professional astronomers do? Well those who took Kepler at all seriously tried to de-nature his results--as had been done early on with Copernicus. Most of these workers were not Copernican anyway. If they were impressed by anything it was the elliptical shape of the orbits. This was worth knowing, because for the first time one could imagine the actual orbit in space. So, and this will not surprise you, they continued to use deferents and epicycles to model and predict the motions, but they adjusted the machinery so that the path traced out would be an ellipse. So much for Kepler's new idea of a causal, celestial physics!

What, finally of the philosophers of nature--were they impressed by Kepler's physical theories? Well, pretty soon, by the 1650s many of them were all going to become mechanists, and all mechanists accepted the Copernican system, so what was their attitude to the great Kepler? They said "Wonderful! What moves the planets? It must be something physical, as Kepler says, but poor old Kepler was a Platonist and believed in weird immaterial causes and forces. We know that all phenomena are caused by mechanical impact of particles or atoms hitting one another. So sure, some physical mechanism or other moves the planets around the sun, but it must be one or another mechanical mechanism of matter in motion." As for the mathematics, that as usual was left to the professional astronomers as we noted just above.

So the great vision is torn to pieces, not taken up whole by anyone. The only person to bring it back together again to any degree is Newton in the later 17th century, not in Kepler's version, but in his own particular way, so that his version is not identical to Kepler's. By that time, everyone accepts the truth in some sense of Copernicanism, and

Kepler's type of neo-Platonism is ancient history. So much for a Whig history of stepwise, linear progress.

Finally, let us note that all three major Copernicans we've mentioned disagree with each other, Copernicus, Kepler, Newton, not to mention that co-opter of Copernican ideas, Tycho Brahe. We may be beginning to wonder what the general term 'the Copernican theory' means. We will address that again later in the final chapters. For now we have to turn the other great early 17th century Copernican, Kepler's luke-warm ally, Galileo.

Figure 1

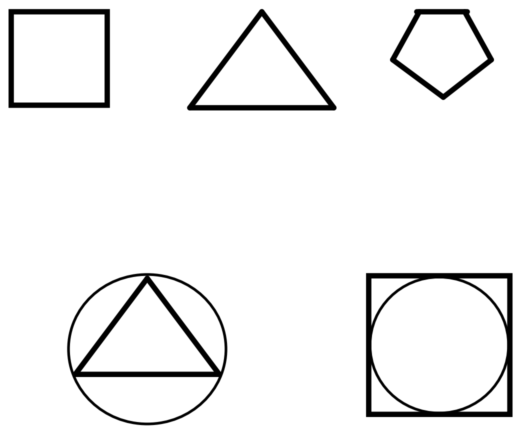
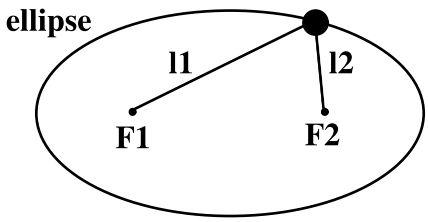


Figure 4 Laws of Planetary Motion 1609

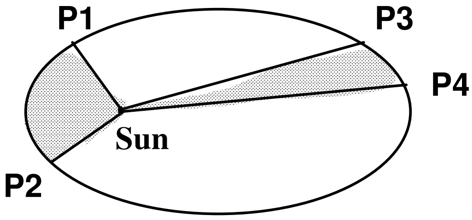
(1) Orbits are ellipses - Sun at one focus

**(2) Line joining Sun-Planet sweeps out
Equal areas in equal times
Suns Force = 1 / distance**



l1 + l2 = constant

Figure 5 Equal Areas Law

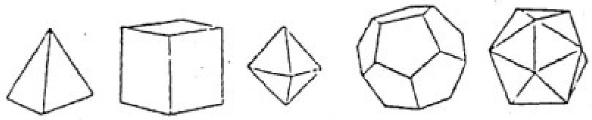


Equal Areas therefore Equal Times

therefore

P2 -> P1 is faster
P3 -> P4 is slower

One can construct any number of regular polygons in a two-dimensional plane; but one can only construct a limited number of regular solids in three-dimensional space. These "perfect solids", of which all faces are identical, are: (1) the tetrahedron (pyramid) bounded by four equilateral triangles; (2) the cube; (3) the octahedron (eight equilateral triangles); (4) the dodecahedron (twelve pentagons) and (5) the icosahedron (twenty equilateral triangles).

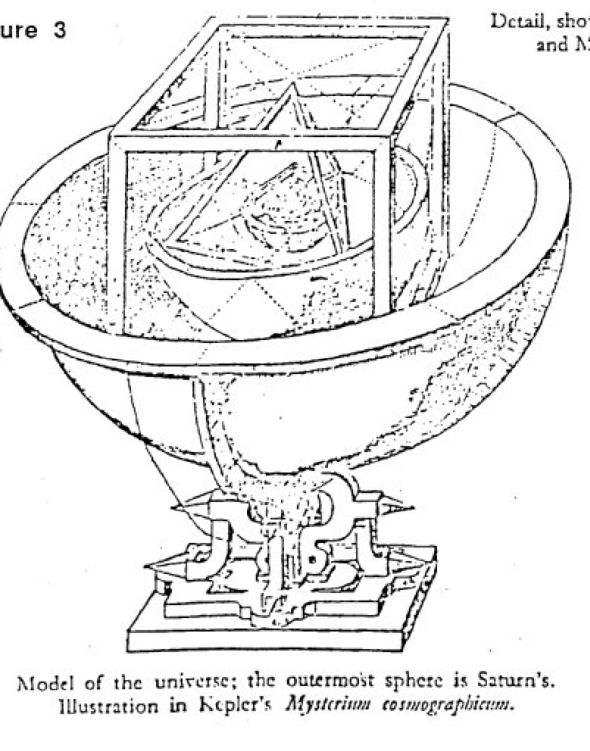


They were also called the "Pythagorean" or "Platonic" solids. Being perfectly symmetrical, each can be *inscribed* into a sphere, so that all of its vertices (corners) lie on the surface of the sphere. Similarly, each can be *circumscribed* around a sphere, so that the sphere touches every face in its centre. It is a curious fact, inherent in the nature of three-dimensional space, that (as Euclid proved) the number of regular solids is limited to these five forms. Whatever shape you choose as a face, no other perfectly symmetrical solid can be constructed except these five. Other combinations just cannot be fitted together.

Figure 2

Detail, showing the spheres of Mars, Earth, Venus and Mercury with the Sun in the centre.

Figure 3



Model of the universe; the outermost sphere is Saturn's. Illustration in Kepler's *Mysterium cosmographicum*.

Figure 6

$$\text{FORCE} \propto \text{SPEED} \propto \frac{1}{\text{DISTANCE from Sun}}$$

Figure 7

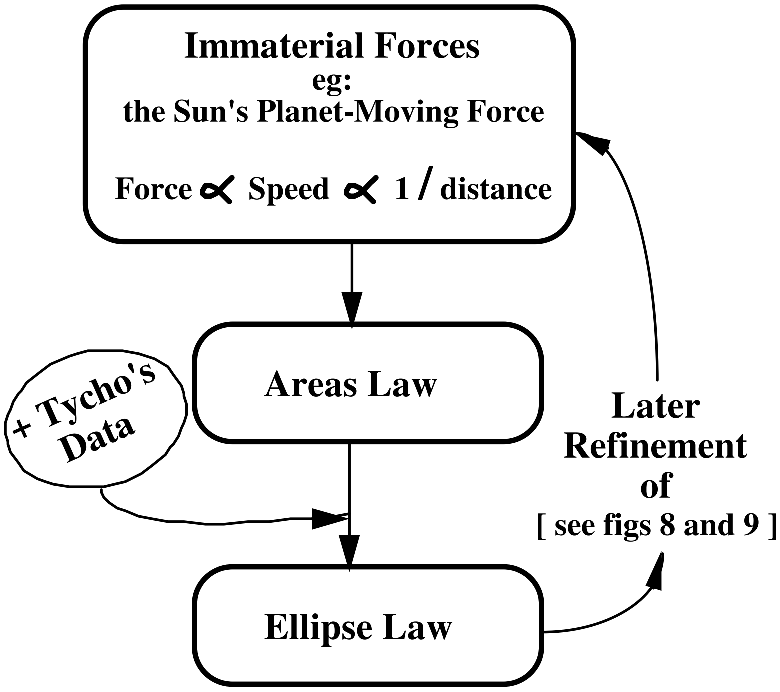
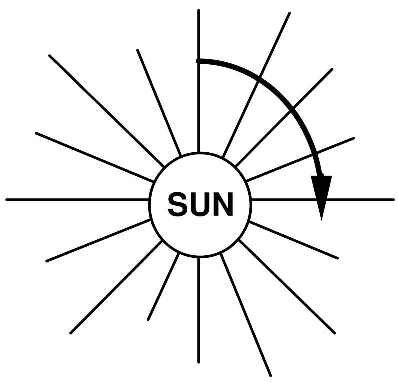


Figure 8 Gilbert. On the Magnet 1600



Newton. b.1642, 1660's Interia & Gravitation

Figure 9

(1) Sun's "sweep" force $\propto 1 / d$
"pushes" planet around

(2) Sun is a north magnetic pole
(south pole at core!)
Earth is a magnet (Gilbert 1600)
with north-south magnetic poles
+ axis at angle to plane of orbit