INVITED DISCOURSES

ASTRONOMY IN ANCIENT GREECE

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Abstract: Science has spread from western Europe where it developed into
recognisably-modern form in the seventeenth century, stimulated by
Copernicus's claim that the Earth is a planet. Copernicus however was
an astronomer in the Greek tradition, whose task was to reproduce the
planetary paths by geometrical constructions using uniform circular
motions. Eudoxus's attempt to do this with nests of concentric spheres
had been superseded by the use of the more flexible techniques necessary
to meet the observational standards of the Hellenistic era. Ptolemy's
Almagest synthesised the Greek achievement but its shortcomings led
Copernicus to make the Earth a planet.

Our purpose this evening is to travel back in time for two thousand
years and more, and to try to enter the minds of those men of the period
who worked to understand the heavens and to explain and predict the
motions of the stars and planets, and who communicated their conclusions
to their fellow-men in the Greek language. And I shall outline reasons
why their achievement was of decisive importance, not only for the
history of astronomy but for the development of modern science as we
know it.

First, some general comments by way of orientation. Those like
myself who spent most of their school years studying Latin and Greek
were encouraged to think that Greek culture came to an end with the
death of Alexander the Great in 323 BC and that of Aristotle the follow-
ing year. But by then Greek astronomy was still in its infancy, and
Claudius Ptolemy, the dominating figure in our story, died around
170 AD, some five centuries later. That is to say, major astronomers
wrote in Greek for at least five hundred years after the decline of
Athenian culture, and for our purpose the years after Christ are as
important as those before.

Nor, for the most part, was astronomy written on the main land of
what is now Greece. Of where the great astronomers lived and worked
we know extraordinarily little, but the places mentioned are mostly in

the eastern Mediterranean: the islands such as Rhodes and Samos, the
towns of Asia Minor, and especially the great centre of learning at
Alexandria. In short, the great astronomers lived in a different age
and in different regions from the great dramatists whose works were
performed in this theatre.

The next point is a little more controversial. Almost every
possible thought, however absurd, occurred to some Greek philosopher at
some time; and occasionally we find suggestions that the Earth is
spinning, or even that it is in some sort of orbit. Archimedes and
Plutarch both tell us expressly that Aristarchus of Samos in the third
century BC proposed that the Earth not only spins on its axis but that
it moves in a circular orbit around the Sun. They do not explain why
Aristarchus proposed this, though the motion of the Earth about the Sun
must surely have involved considerations of the apparent motions of the
planets. Nor do they make it clear whether Aristarchus believed the
Earth to be in truth moving about the Sun, or whether he merely argued
that this would be one way of accounting for the observed facts.
Aristarchus had inherited a speculative tradition, but by the third
century BC astronomy was becoming more sober and serious and technical,
and we know of only one very minor figure who took the suggestion of
Aristarchus seriously. That is to say, we make the mistake of looking
at Greek astronomy with our eyes rather than theirs, if we seize on
Aristarchus as a precursor of Copernicus, and exaggerate the importance
of an hypothesis whose impact in Antiquity was almost nil. Instead, we
must understand their astronomy in terms of the questions they thought
important, the evidence at their disposal, and the conceptual and
mathematical tools they could deploy. To see the problems as they saw
them is not easy; but it is more difficult still to rid ourselves of the
ethical conventions of the science of today: the duty to say what is our
work and what we have taken from the writings of others, to say what is
a genuine observation and what is an observation adjusted to fit a
theory and what is no observation at all but a straightforward calcula-
tion. But here too one can say that the historian who condemns past
astronomers as fools or criminals is most probably condemning himself
as an historian.

Next, a word about historical records. For any period, records
survive of only a minute fraction of the events that actually take
place -- will any record survive to tell your biographer what you had
for breakfast today? The historian has no possibility of access to
events of which no records survive, and he must accept that when he has
made sense of the surviving records then he has done all that is
possible. Even so, in the modern period the surviving records are often
overwhelming in number, and the historian singles out an incident here
and there to illustrate his general theory. But when we turn to the
study of Antiquity, the situation is the very opposite. Very little
has come down to us, and we must make the most of the fragmentary
records that we have. There are several reasons for this scarcity of
source material. With few exceptions, what we have of Greek astronomy
is not original documents contemporary with the author, but copies of

copies of copies, laboriously and expensively made, and perhaps involv-
ing one or even several translators. In most cases a work was never
widely in demand, or if it was then the demand fell off with time, so
that no copy has come down to us and the work is lost. This can apply
even to works of the first importance, if their content is assimilated
into a later and even more successful work. For then there is no
longer any purpose in the potential reader's paying good money to recopy
the earlier work, which therefore vanishes. This happened in Greek
mathematics when Euclid's Elements synthesised the achievements of his
mathematical predecessors: the writings of these predecessors thereupon
vanished. But the historian of mathematics is lucky, in that Euclid
wrote about 300 BC, when some of the greatest mathematicians of
Antiquity were still to come. Ptolemy wrote his Almagest in the middle
of the second century AD; he drew extensively on the work of his great
predecessor Hipparchus, and so of the writings of Hipparchus we possess
only one minor example. The very success of Ptolemy as a synthesiser,
coming at the end of the high period of Greek astronomy, brought about
the destruction of the works of even his greatest predecessors; and
this apparent dearth of predecessors in turn enhanced Ptolemy's own
stature in the eyes of later civilisations.

     With these preliminaries, let us quickly travel back in time from
the present, beginning with a word about science and scientists in the
modern world. We have at this General Assembly astronomers from every
nation on earth, sharing in a common enterprise. There is world-wide
agreement about what it is to be a scientist -- what a scientist does,
the questions he asks, the kind of answer that is acceptable, and the
methods for arriving at such an answer and communicating it to other
scientists. These agreements are inculcated in our education, and
enforced by appointments committees to posts for teaching or research,
by referees who control access to scientific journals, and by the
electors to membership of scientific societies. Today this agreement is
worldwide. But if we travel back in time to the year 1700, say, we find
modern science only in western Europe. In England and France there are
major scientific societies -- the Royal Society and the Académie des
Sciences -- and scientific journals; scientific teaching posts in
universities, and research institutions such as the Greenwich and Paris
Observatories. Most important of all, there is the Principia of Isaac
Newton which the eighteenth century would take as a model of a mature
science. But the rest of the world has yet to learn from western
Europe what science is.

     If we go back another hundred years, to 1600, we find no major
scientific societies, no scientific journals, and only here and there
a post where an astronomer or mathematician might make a career. But
two men are at work whose achievements would set physical science on
the path to Newton's Principia. Galileo would soon use the telescope
to extend the range of the human senses, something no Greek would have
envisaged, and he would become the first human being to see mountains
on the Moon, and phases of Venus, the satellites of Jupiter, and so
forth. Armed with this evidence against the old world-picture of

Aristotle and Ptolemy, he became a militant Copernican and set himself
to create a physics in which it made sense for the Earth to be in motion
about the Sun while we passengers on Earth are totally unaware of it.
Kepler was a convinced Copernican from his youth, and he would soon use
the accurate observations of Tycho Brahe to develope a profoundly new,
dynamical astronomy within which each planet would orbit the Sun in a
single curve, the ellipse studied by the mathematicians of Antiquity.

In the work of Galileo and Kepler we find powerful new elements
marking a fundamental advance beyond anything present in Copernicus
only a few decades earlier. Copernicus's De revolutionibus (1543) is
thoroughly Greek in spirit and method; it is very obviously modelled in
layout on Ptolemy's Almagest, addressing the same problems and offering
the same kind of answer by means of similar techniques. Indeed, in some
ways it was more faithful to the totality of Greek natural philosophy
and astronomy than was Ptolemy's Almagest. Copernicus was not the first
of the moderns but the last of the medievals, and last of the astronomers
in the Greek tradition; yet his claim that the Earth is a planet
convinced both Kepler and Galileo and helped spark off the Scientific
Revolution that taught first western Europe and then the whole world
what science is. This, in brief, is why Greek astronomy is fundament-
ally important in the whole history of science.

The basic aim of Copernicus's De revolutionibus is to use combina-
tions of uniform circular motions to provide geometrical constructions
that would accurately reproduce the observed motion of each planet across
the sky. He was, in fact, answering the challenge said to have been
thrown down by Plato in the first half of the fourth century BC: "By the
assumption of what uniform and orderly motions can the apparent motions
of the planets be accounted for?"

The assumptions underlying Plato's question are very remarkable
indeed. First of all, the universe is assumed to be a cosmos. Today we
do not link the astronomical term 'cosmos' with the cosmetics that a
lady uses to perfect the beauty and harmony and symmetry of her appear-
ance, but the root word is the same. A cosmos is first of all a
rational universe, one that the human intellect can penetrate. It is
not the domain of the gods with their whims and fancies, their play-
things and their enemies, gods whose behaviour a mortal man can neither
control nor predict. There can be a science of the universe because the
universe is a cosmos. But a cosmos is not merely rational; it has
beauty and harmony and symmetry. Copernicus found Ptolemy's treatment
of the planets one by one unsatisfactory because there was no perception
of the unity of the universe; the result of assembling the various
independent bits would be, he said, "monster rather than man". Kepler,
in his first publication, believed he had penetrated the mind of the
divine geometer who created the universe, when he found that the planet-
ary orbits were spaced out on the pattern of a nest of regular solids and
spheres. The cosmos had a long and important history, and the conviction
on the part of the early Greeks that the universe is a cosmos set the
scene for the science of astronomy.

At the outside of the cosmos was the sphere of the heavens. We are
so used to working with spherical geometry that we think it self-evident
that the heavens appear spherical to the observer, but a study of other
early civilisations shows that this is far from being the case.
Curiously, at the other extreme, many people today are convinced that
the spherical shape of the Earth is an early modern discovery and that
explorers like Christopher Columbus feared they would sail off the edge
of a flat Earth. In fact, the spherical shape of the Earth was known to
Pythagoreans long before Plato, and in the writings of Plato's pupil,
Aristotle, which were so central to medieval education, we have several
proofs of this: that the shadow of the Earth during an eclipse of the
Moon is always circular in outline, and that the stars are seen
differently as we travel north and south. Indeed Aristotle quotes a
value for the circumference of the Earth that is too large, but only by
a factor of less than two. The Greek sense of symmetry demanded that
the spherical Earth be at the centre of the spherical heavens, and there
was nothing about the appearances to contradict this. Plato's challenge,
therefore, assumed a cosmos that was lawlike, and comprised a spherical
Earth at the centre of a spherical heavens.

Now the stars goes round us every day, and since the Greeks were
the boldest, not to say the most irresponsible of speculative thinkers,
a number of early philosophers suggested that the Earth itself might be
spinning or otherwise in motion. Since Aristotle's method of exposition
is to give the views of others before giving his own, he sets out these
theories, thereby ensuring that every medieval and Renaissance student
of astronomy considered them too. But Aristotle, like other Greek
writers, has one especially decisive argument against the motion of the
Earth; and although it is not the custom in Invited Discourses to
perform experiments, I would like to reproduce the Aristotelian test,
and prove to you experimentally that the Earth is indeed at rest. I
take this heavy stone, and I throw it straight up in the air. You will
see that it falls back into my hand, and this proves that my hand did
not move during the time that the stone was rising and falling. If the
Earth had been in motion, and I and my hand with it, then my hand would
have moved on in the second or two that it took the stone to rise and
fall back again to the place from which it had been thrown. Instead,
when it arrived back again, there was my hand, ready to catch it. To
quote Aristotle: "heavy bodies forcibly thrown quite straight upward
return to the point from which they started" (De caelo, 296b). (It goes
without saying that post-Newtonian science provides a theoretical frame-
work within which the experiment by no means proves that the Earth is at
rest. Modern theory benefits from the heroic efforts of Galileo and
others to make dynamical sense of Copernicus's claim. But as historians
we have to see the experiment through Greek eyes, and interpret it within
the context of their theory, not ours. Within that context, the experi-
ment decisively proves the Earth is at rest.)

Aristotle, even more than Plato, emphasises for us the contrast
between Earth and heavens. On Earth there is coming to be and passing
away, life and death, and this is reflected in the fact that natural

movements (a stone in falling, smoke in rising) take place in a straight
line, towards or away from the centre of the Earth, which is also the
centre of the universe. And such movements are temporary: the stone
stops falling when it has fallen as far as it can. By contrast, in the
heavens everything is eternal, stars never appear or disappear, and this
is expressed in their movements, regular uniform cyclic movements that
of their nature continue endlessly without change.

Mainstream Greek astronomy, then, accepted a spherical Earth at
rest in the centre of a spherical sky, with almost all the stars
rotating daily about the Earth with a common and unchanging cyclic
motion. Almost all the stars, but not quite all. Seven stars seemed
irregular, whimsical, lawless in their movements: namely, the Sun, the
Moon, Mercury, Venus, Mars, Jupiter and Saturn. These were the
'wandering stars', in Greek planetes, 'planet'. These seven planets
seemed exceptions to the otherwise regular and lawlike cosmos. Plato's
challenge was to show that the seven wanderers are not true exceptions
but are equally lawlike and geometrical and regular in their motions -
in other words, that the regularity is there, though it is more complex
than with the fixed stars.

What kind of answer is Plato prepared to accept? The "uniform and
orderly motions" he requires must in fact be combinations of uniform
circular motions. Just as some recent cosmologists have insisted that
a theory of the history of the universe must be without any special
moment in time, because this is the way things must be, so Greek
geometers and astronomers had a profound conviction that the heavens
move with uniform circular motions: the cosmos simply is that kind of
realm, and eternal, unchanging circular motions are the only motions so
fundamental, so basic that of them no further questions can be asked.

The challenge posed by Plato shows a mature attitude to astronomy
as an intellectual enquiry: an apparent anomaly in an otherwise
satisfactory theory is to be resolved along agreed lines. The solution
proposed by Plato's contemporary, the great mathematician Eudoxus, and
preserved for us by Aristotle, is a brilliant mathematical tour de force;
in that, although proceeding along what we know to be quite the wrong
lines, Eudoxus generates the observed movements of each planet in
qualitative outline by means of an elegant and simple geometrical
construction. Each of the seven planets is thought of as attached to
the equator of a sphere centred on the Earth and spinning about its
poles with a uniform angular velocity. These poles are thought of as
attached to a second sphere, outside the first and concentric with it,
and spinning about different poles with a uniform angular velocity. The
motion of the planet will of course be compounded from the motions of
the two spheres.

Outside the seoond sphere is a third, again centred on the Earth.
The poles round which the second sphere spins are attached to the third
sphere, which spins about yet another axis, and again with a uniform
angular velocity. This completes the geometrical model for the Sun and

Moon, but for the other five planets there is for each a fourth sphere, concentric with the other three and carrying the poles of the third sphere.

     We have for each planet a beautifully simple and elegant geometrical model, consisting of either three of four spheres, all concentric with the centre of the universe which is the centre of the Earth, and all spinning with uniform angular velocities. In the case of the Moon, the outermost sphere spins once a day about the poles of the celestial equator; the middle sphere spins about the poles of the ecliptic once every 18.6 years, the Saros period within which eclipses usually recur; the third sphere is inclined slightly to the second, and carries the Moon round once every synodic month. This model worked surprisingly well, much more so than that of the Sun which follows a similar pattern. But the brilliance of Eudoxus in geometry, if not in astronomy, is shown in his models for the other planets. Again, the outermost of the spheres (of which now there are four for each planet) reproduces the daily spin of the entire sky, while the next sphere carries the planet along the ecliptic. The job of the other two spheres is to reproduce the retrograde loops that had earned the wandering stars their name. The mathematics underlying this was recovered less than a century ago. The axes about which the two spheres spin are inclined slightly to each other, and the two spheres rotate with equal and opposite angular velocities, completing one rotation in the synodic period of the planet. It turns out that the curve produced by these two motions is a kind of figure-of-eight, the intersection of a sphere and a cylinder tangent to the sphere at one point. As a result, the four spheres for Jupiter, say, reproduce the daily motion of the planet and its motion along the ecliptic compounded with a regular figure-of-eight that gives the planet a motion in latitude as well as causing it to retrograde from time to time. With three spheres for the Sun and Moon, four each for the other five planets, and one for the fixed stars, Eudoxus needed a total of only 27 spheres; and of these, no fewer than eight simply reflected the daily spin of the Earth.

     Here we have, for the first time in history, a geometrical model which could in principle reproduce the motions of the planets for all time in the future -- and thereby, of course, confirm that the world is indeed a lawlike cosmos. Eudoxus the geometer expressed the mathematical laws governing the motions of the planets. In all probability he did not intend these spheres to be thought of as physically real, so that he was not theorising about the <u>material</u> structure of the heavens. Aristotle was soon to do this, making each nest of spheres physically real and introducing additional "cancelling-out" spheres between one nest and the next so that unwanted motions would not be transmitted down through the system. To the natural philosopher, these concentric spheres were profoundly attractive as a basis for the explanation of the cosmos: spheres spinning uniformly about the central Earth, as we clearly observe the sphere of the fixed stars to spin, hardly needed further explanation, so thoroughly were they in harmony with the rest of cosmology. Indeed, a last attempt to construct such a universe was made

in the time of Copernicus, and in the intervening centuries the natural
philosophers were never really at ease with anything else. Yet, as we
can see, Eudoxus was on fundamentally the wrong track, and there was
never any hope of the observed motions of the planets being <u>accurately</u>
reproduced along these lines. Indeed, we might say that his
constructions were designed to be admired rather than used as a serious
astronomical tool. And so the mathematical astronomer was soon to part
company with the natural philosopher.

The parting happened all the more rapidly because in the next
generations Greek astronomers had access to the arithmetical astronomy
of the Babylonians. The finest period of Babylonian astronomy is in the
last three centuries before Christ -- later, that is, than Eudoxus. But
their records of eclipses went back to the eighth century. Among the
motivations for their interests in astronomy were the lunar calendar
they used, and the widespread commitment to astrology which soon spread
to the Greeks and led them too to demand accurate planetary tables. The
Babylonians were blessed with the sexagesimal notation for numbers, the
base of sixty which the Greeks soon took over into astronomy and handed
down to us. This enabled the Babylonians to handle complex arithmetical
operations with ease, and their astronomy involved using their
arithmetical skills to predict new moons, eclipses and so forth. Where
the Greeks sought to reproduce the motion of a planet at all times by
their geometrical models, the Babylonians used their arithmetic to
calculate special events; and, as far as the evidence goes, where the
Greeks sought to understand, the Babylonians served practical needs.
But what the Babylonians did, they did with ruthless brilliance. For
their lunar calendar they needed to control the speed of the Sun along
the ecliptic. This speed varies throughout the year, increasing for a
time and then decreasing again. The Babylonians approximated to this by
supposing the Sun to move for half the year with one constant speed, and
then for half the year with another constant speed, with an instantaneous
jump between the two; or by supposing the Sun to increase speed uniformly
for six months and then decrease for six months, in what we would think
of as a zig-zag function; and they then used their arithmetical skills
to make the resultant calculations. Clearly they did not suppose the
real Sun moved in either of these ways. They were simply arriving at a
desired practical result with sufficient accuracy.

Accuracy was just what Eudoxus's nests of spheres did not provide.
His approach prevented the Sun or the Moon (or the other planets) from
varying their distance from Earth, which they seem to do. The planetary
loops we actually observe do not have the regularity of the loops
generated by Eudoxus's spheres. And a mathematical investigation shows
that while parameters can be chosen that work reasonably well for
Jupiter and Saturn, the situation is hopeless for Mars, Venus and
Mercury. And so it is not surprising that Greek astronomy moved away
from concentric spheres, while still honouring the rule that the motions
used must be uniform and circular. It seems that around 200 BC,
Apollonius, one of the greatest mathematicians of Antiquity, proposed
the use of eccentric circles -- circles on which the planet moves with

uniform angular velocity, but where the centre of the circle is no
longer the Earth itself (which is therefore 'eccentric'). This
obviously would allow the planet to vary in distance from the Earth.
Secondly, Apollonius proposed to allow the planet to move uniformly on a
little circle (or 'epicycle'), whose centre moved uniformly on a large
circle centred on the Earth. Here, of course, Greek astronomy hit upon
a most promising line of development. For Venus, say, orbits the Sun in
an ellipse that is not far from being a true circle, and the Sun appears
to orbit the Earth in an ellipse that is not far from being a true
circle; so that the orbit of Venus viewed from Earth is indeed epicyclic
to the first approximation.

In the short term, however, it was the Sun and Moon that were to be
treated with the new mathematical tools. Hipparchus of Rhodes, who
lived in the second century before Christ, was the first Greek to be
both a careful observer and a competent mathematical astronomer. He
compiled a catalogue of over eight hundred stars, and Pliny tells us
this was because Hipparchus believed a new star had appeared but he had
no existing catalogue by which to prove its novelty. He is said to have
discovered the precession of the equinoxes. In order to facilitate the
determination of the difference in geographical longitudes between two
places, he prepared a table of eclipses for the next six hundred years,
so that observers in each place would be ready to record the local time
at which the eclipse occurred and so determine the time difference
between the two places. And he used the tools of Apollonius in order to
construct the first reasonably satisfactory geometrical models for the
motions of the Sun and Moon.

Apart from one short work, all the writings of Hipparchus have been
lost -- except, that is, for those which have been assimilated into and
developed in the work of Ptolemy. Ptolemy, writing in the middle of the
second century after Christ, compiled in his Megale Syntaxis an elaborate
treatment of all the planets, a treatment that Copernicus himself admits
could be amended to generate acceptably accurate planetary tables. The
Almagest, as we know it, rendered all previous works in the field
obsolete, causing them to vanish, leaving the Almagest appearing all the
more astonishing an achievement for the absence of visible predecessors.
Of what had happened in astronomy in the interim we know little. In his
lunar theory Ptolemy bases himself on Hipparchus, but he finds that the
earlier theory cannot account for evection which Ptolemy discovered from
observations. Ptolemy's own theory of the Moon is too elaborate to
discuss here, but if taken at face value it would involve the Moon vary-
ing its distance from the Earth by a factor of two, with of course a
similar variation in its apparent radius. Obviously this does not
happen in reality, and so we see here the over-riding concern of the
practising astrologer (Ptolemy is the author of an elaborate textbook of
astrology) for the position of the Moon against the background of the
stars.

It was no doubt because of his pressing practical need for a
geometrical machinery that would quickly and accurately compute planetary

positions, that Ptolemy allowed himself to depart from the philosophers'
rule that only uniform circular motions can occur in the heavens. If we
take advantage of hindsight we can understand why the Ptolemaic device
termed the 'equant' was so economical. Consider Kepler's laws that tell
us that the Earth moves in an elliptical orbit around the Sun, with the
Sun at one focus of the ellipse, and that the radius vector from the Sun
to the Earth traces out equal areas in equal times. As far as the
observational appearances go we can interchange the Sun and the Earth,
and think of the Sun moving round the Earth in an ellipse with the Earth
at a focus, the radius vector tracing out equal areas in equal times as
before. Now consider the view from the empty focus of the ellipse.
When the Sun in its orbit is near the empty focus, its linear velocity
is least, but for an observer at the empty focus this is compensated for
by the nearness of the Sun. Conversely, when the Sun is nearest to the
Earth in its orbit, its linear velocity is greatest, but for the observer
at the empty focus this is compensated for by the greater distance of
the Sun. To sum up, the passage of the Sun across the sky will appear
to an observer at the empty focus to be very close to uniform angular
velocity.

     Now the fact that the true orbit of the Sun around the Earth is an
ellipse rather than a circle is of secondary importance; it is the
variations in speed that are more obvious. And so we conclude that we
can approximate well to the observed motion of the Sun across the sky if
we consider the Sun to be moving on a circle whose centre is someway
from the Earth, and to be moving with such a varying speed that when
viewed from a point equidistant at the other side of the centre of the
circle, the Sun appears to be moving with uniform angular velocity.
Such a point is an equant point, and we note that (i) this requires the
Sun to move with variable velocity, contrary to the prescriptions of the
philosophers, and (ii) thanks to Kepler, we can see why this device was
useful. By using it as one of his permitted mathematical tools, Ptolemy
achieved his practical aim of facilitating the calculation of planetary
tables; but he created a gulf between the philosophers, or cosmologists,
and the mathematical astronomers. The philosophers were less than happy
with circles and circular motions that were not centred on the Earth;
with non-uniform motions introduced by Ptolemy, it was clear beyond
doubt that the real cosmos was not to be found in the work of the
mathematical astronomers. The unease at this must have been felt by
every student in the late medieval universities, and it is a source of
pride to Copernicus that he has succeeded in developing accurate and
economical geometrical models without the device of the equant.

     Ptolemy's achievement in creating for each planet a geometrical
model that enabled its position to be computed with accuracy for
centuries to come was extraordinary. But in the Almagest there is no
unified system. There are common techniques, of course, and a period of
one year keeps cropping up, to arouse the curiosity of later medieval
astronomers, but there is no integrated system and certainly no physical
model of the heavens. This Ptolemy provided in a late work, the
Planetary Hypotheses, that was unknown to Copernicus and his

contemporaries. Here we are indeed given a physical model of the
universe, in which the epicycles are like ball bearings running in
grooves. Ptolemy adopts a particular order for the planets (Moon,
Mercury, Venus, Sun, Mars, Jupiter, Saturn, fixed stars), and he assumes
that at every height from the Earth it is possible to have one and only
one planet. That is to say, the maximum height of the Moon above the
Earth equals the minimum height of Mercury, the maximum height of
Mercury equals the minimum height of Venus, and so on.

To calibrate this system Ptolemy needs the distance of the Moon
from the Earth. Several earlier writers had tackled this problem, and
from Aristarchus in the third century BC we possess a mathematical
treatise showing how it might be solved. Aristarchus's method involved
measuring the angle Moon–Earth–Sun when the Moon is at quadrature, that
is, when the angle Sun–Moon–Earth is known to be right angle. The
observation gives him the shape of the triangle and so the relative
distances from Earth of the Sun and the Moon; and further information
about the apparent diameters of the Sun and Moon and about the width of
the Earth's shadow as compared to the diameter of the Moon gives him the
distances of the Sun and Moon as multiples of the Earth's diameter. This
was a brilliant demonstration of the ability of mathematics to master
cosmic dimensions, but hardly the technique of a practising astronomer.
In the Almagest Ptolemy uses parallax observations to derive the
distance of the Moon, and from this he calibrates the planetary system
set out in the Planetary Hypotheses. By an extraordinary coincidence,
the distance of the Sun then turns out to be close to that he derives
by a totally independent method in the Almagest, which does nothing to
diminish Ptolemy's confidence in the validity of his system. The fixed
stars prove to lie at some twenty thousand Earth radii, or well over one
hundred million kilometres, so that the Ptolemaic universe is not small.

For fourteen hundred years, Ptolemy's Almagest was without rival,
until the invention of printing in the fifteenth century gave a boost to
the study of technical astronomy. Copernicus, working the early
sixteenth century, saw in the Almagest an extraordinary mathematical
achievement that was capable of revision to an acceptable standard of
accuracy, but was nevertheless defective in important ways. In
particular, it treated each planet independently and on an ad hoc basis,
giving the same period of one year to Sun, Venus and Mercury, and
leaving even the very order of the planets open to argument. He realised
that if the Earth is considered a typical planet, and the other planets
are observed from this moving platform, then the true periods of the
planets and their distances from the Sun can be established and these
two sets of numbers shown to fall into a single harmonious pattern. The
division of the planets into those always near the Sun and those not so
is no longer surprising and puzzling but actually to be expected. And
the curious retrograde motions of the planets, and when and for how long
they occur, are all explained, once one accepts that we observe them
from a moving platform. All this he shows in Book I of De revolutionibus,
and no doubt Plato would have been astonished but delighted with this
response to his challenge, with the true harmony of the universe revealed.

Then, in the remaining books of De revolutionibus, Copernicus shows how
the heliocentric approach can be made the basis of a technical astronomy
more accurate than Ptolemy's, with numerous epicycles and eccentres but
without the illegal equant.

   De revolutionibus is clearly a mathematical treatment of the
apparent motions of the planets in the tradition of the Almagest,
though free of some of the defects that had made the Almagest itself
unacceptable to the natural philosophers. Unlike its predecessor, it
offers a heliocentric cosmology, and even some hints on the physics of
the Earth's motion. It is, one might say, as far as Greek astronomy
could go. Within two generations came the obsessive search of Tycho
Brahe for observational accuracy; the telescope of Galileo, and his
theory of uniform motion as a state similar to the state of rest; and
the dynamical astronomy of Kepler with its consequent emphasis on the
actual orbit of a planet rather than on possible components from which
the orbit might be constructed. Between Copernicus and Kepler is a
greater intellectual gap than between Ptolemy and Copernicus. Greek
astronomy, culminating in Ptolemy and Copernicus, had shown the power of
mathematical models in explaining and predicting the motions of the
planets, and had indicated in De revolutionibus the need for a new
physics in which the motion of the Earth was no longer absurd. Greek
astronomy by itself was not a sufficient condition for the development
of modern science; but in historical terms it was a necessary one.