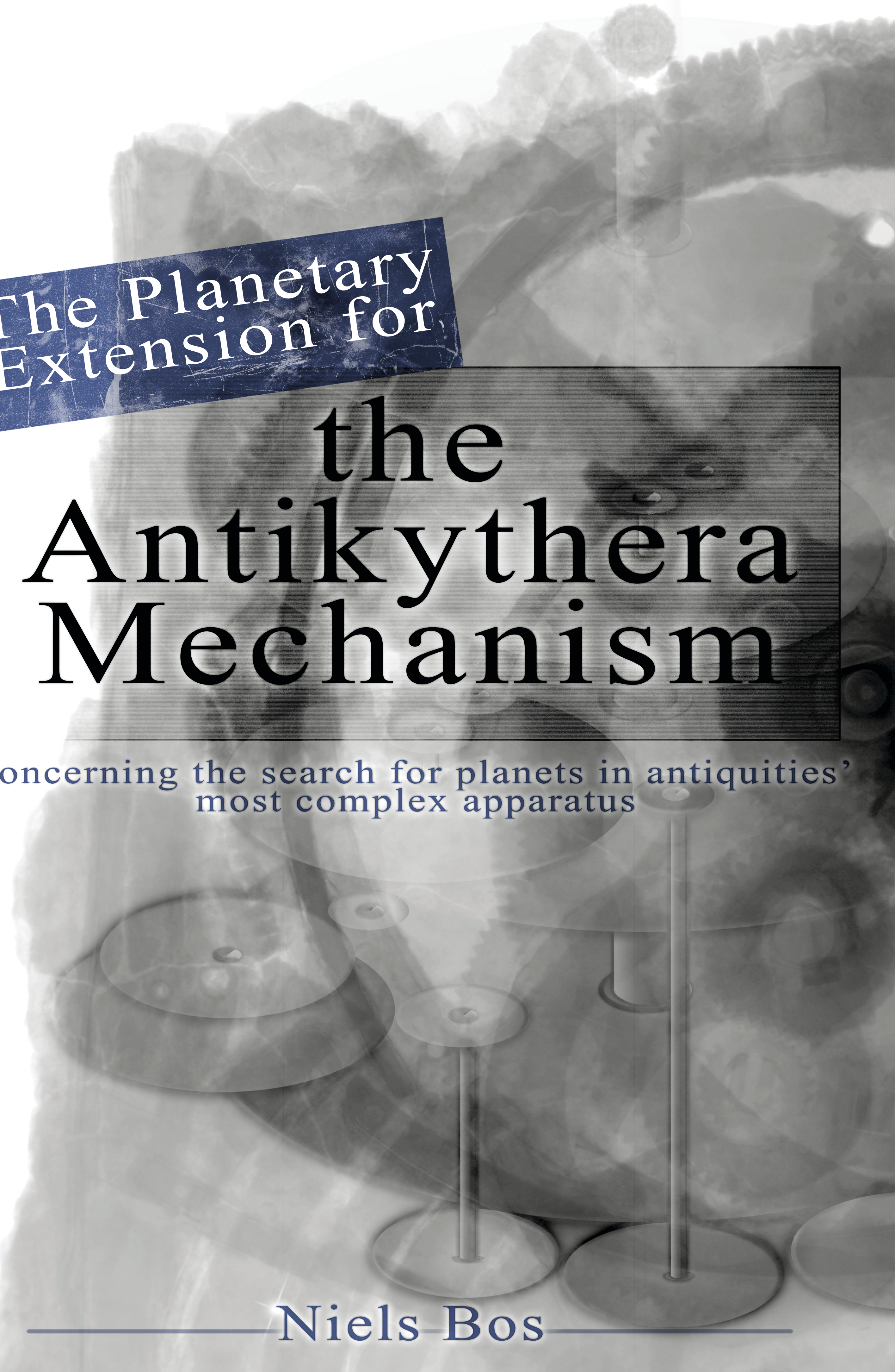

The Planetary Extension for the Antikythera Mechanism

Concerning the search for planets in antiquities' most complex apparatus

Niels Bos

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——— *by* ———

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Abstract

What may well be the most extraordinary and mysterious surviving artifact from the ancient Greek world, is the 'mechanical computer' now known as the Antikythera Mechanism. This amazing 2,000 year-old clockwork device is dated to approximately 150 – 100 BC., and was presumably used to calculate complex astronomical time-reckonings.

In 1901, the device was salvaged from the remains of a Roman merchant ship, in the Eastern Mediterranean. It was a stunning discovery. Up to that time, scholars were completely ignorant of the fact that antiquity had produced such intricate gearing mechanisms. By now, we know that the technological sophistication of the device is an order of magnitude more complicated than any surviving instrument from the following fourteen centuries.

Research indicated, that the Antikythera Mechanism was able to present the time, with respect to several astronomical and social cycles. It also displayed the time of year, as well as the positions of the mean Sun and the Moon, through exceptional series of gear trains.

In this master thesis, we investigate the research question whether it was possible that the mechanism reproduces the motions of the five known planets of antiquity: Mercury, Venus, Mars, Jupiter and Saturn. And if so, how such a design would be fulfilled.

There are significant arguments advocating the existence of the representation of the planets. Nevertheless, there is no solid evidence, found in the artifact.

During our research, we find that there is sufficient ground to assume, that a planetary extension for the Antikythera Mechanism could have existed.

After investigating the history of Greek astronomy, we investigate the epicycle theories held by in the Hellenistic era, as well as the modern reconstructions of the Antikythera Mechanism. From this, we are able to extrapolate a schematic gearing design for each of the planets and the True Sun within the planetary extension of the mechanism, along with a qualitative and statistical justification for our method of design.

Contents

Chapter 1

Introduction

1.1 The computer of the classical world

What may well be the most extraordinary and mysterious surviving artifact from the ancient Greek world, is the 'mechanical computer' now known as the Antikythera Mechanism. This amazing 2,000 year-old clockwork device, which was presumably used to calculate complex astronomical time-reckonings, has been a tantalizing puzzle for scholars and scientists over more than one century.

The device was recovered in the Greek Mediterranean in 1901 as a single corroded bronze lump, during the salving of the shipwreck from a Roman cargo ship which had sunken around 80 – 50 BC. (Price, 1974). A first glimpse of its true complexity was displayed several months after the recovery, when it split apart due to its exposure to the dry Greek air. Some thirty gear wheels were revealed.

It was a stunning discovery. Up to that time, scholars were completely ignorant of the fact that antiquity had produced intricate gearing mechanisms, long before anything comparable.

Being the extraordinary item that it is in the scientific world, the research the Antikythera Mechanism gained followed an intriguing path. Over the early twentieth century, the found fragments of the mechanism certainly did not seem to have been given the prominence one would expect. Over the last couple of decades, however, the device had been subject to the extensive research it deserves. By now it has been established that it is an order of magnitude more complicated than any surviving mechanism from the following millennium. Perhaps as perplexing is the fact that it is without any precursor (Seabrook, 2007).

The first well documented western device, that shows some resemblance to the Antikythera Mechanism, is an astronomical clock made in the early fourteenth century. It was made in England by Richard of Wallingford, the Abbot of St. Albans (North, 2005). This clock was called the Albion – The 'All-by-One.' Another early well-known planetarium and clockwork was made mid-fourteenth century by the Italian Giovanni de' Dondi, of Padua. This clock is known as the Astrarium (Baillie et al., 1974). Still, these two giant achievements were constructed fourteen century after the Antikythera Mechanism (Singer et al., 1957b).

All that remains of the device today, are eighty-two fragments of flaking bronze, forming the accommodation for the thirty gear wheels (Freeth et al., 2006). While

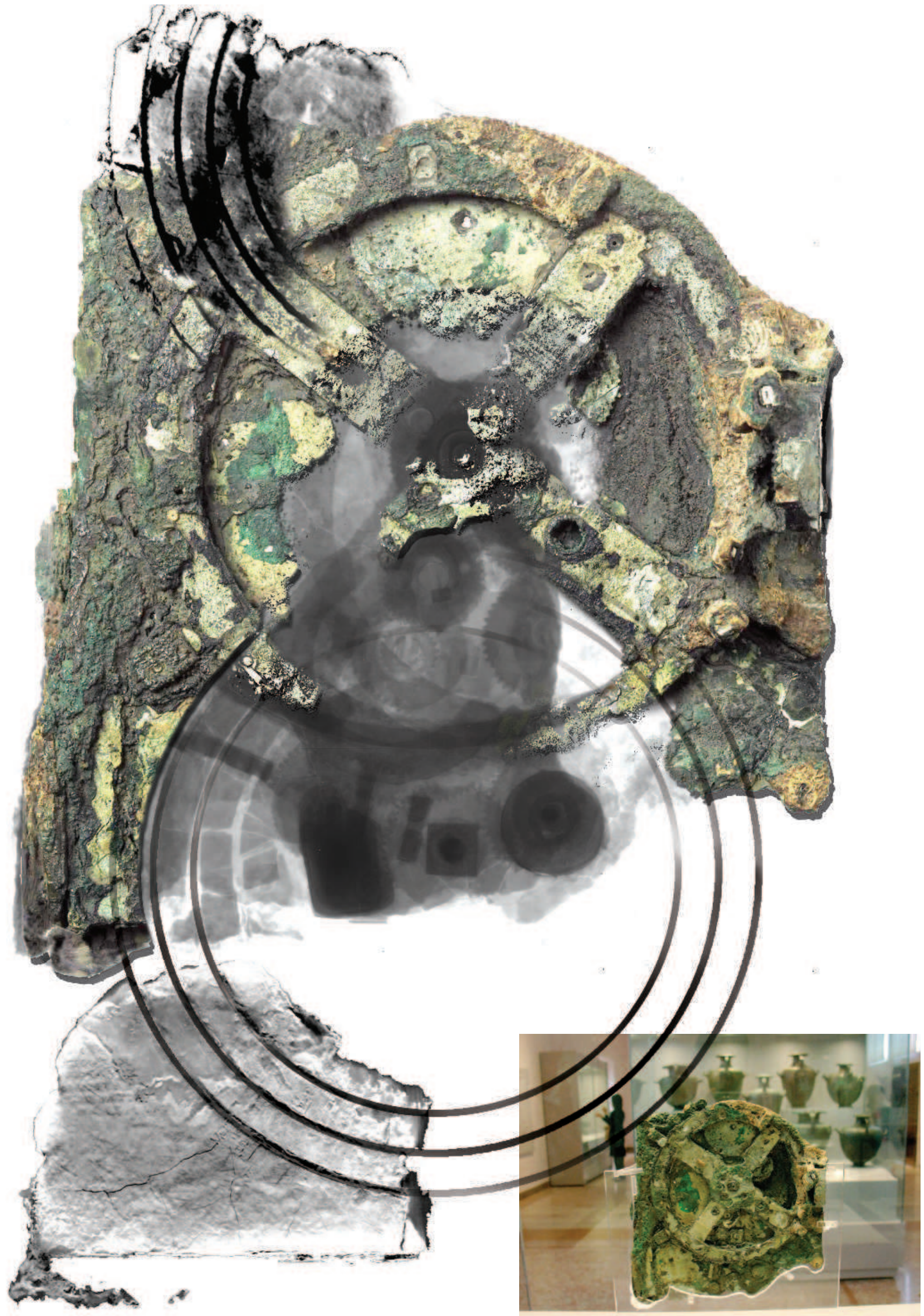


Figure 1.1: A collage of photographs and radio-graphic images from the surviving fragments. The image illustrates the fascinating complexity of the device. It provides a view of the inner regions of the mechanism, uncovering a multitude of different gears, axes and additional features. Also, parts of the dials from the outer plates of the mechanism can be noticed. A picture of the largest surviving fragment is shown in the bottom right corner, as it is displayed in the National Archaeological Museum of Athens.

trying to decode the mechanism's inscriptions and functions, researchers from a wide variety of different scientific disciplines managed to relate the gear train ratios to astronomical cycles of the Sun and the Moon. The overall architecture of the device was published in 1974, in a pioneering study by Price (1974). However detailed and meticulous the study was, the functions of nearly all of its dials have been radically reassessed since then.

Figure 1.1 shows a collage of photographs and radio-graphic images from the surviving fragments. The image illustrates the fascinating complexity of the device. It provides a view of the inner regions of the mechanism, revealing a multitude of different gears, axes and additional parts. Also, parts of the dials from the outer plates of the mechanism are superimposed. A picture of the largest surviving fragment can be seen in the bottom right corner of Figure 1.1, as it is displayed in the National Archaeological Museum of Athens.

The Antikythera Mechanism is presumed to have been made around 150 – 100 BC. (Freeth et al., 2008). Most of the reconstructions of the device consist of a wooden case, with a size of about 33 $cm \times 18$ $cm \times 10$ cm, where the last quantity is the most uncertain one. It has an input on one side, which was probably used to turn by hand, and drive the rest of the gears via a crown gear. On its front and back faces are a number of output dials. Figure 1.2 shows a reconstruction of the mechanism, without its wooden case, but clearly illustrating the locations of the engraved front and back dials.

The front dials consist of two large concentric displays, a Zodiac dial with the

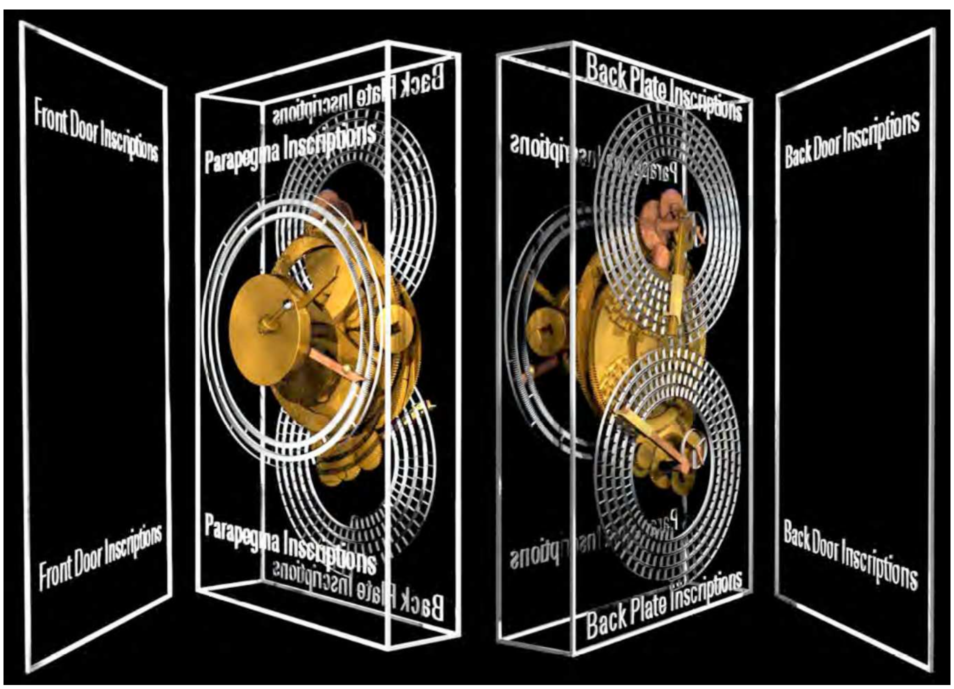


Figure 1.2: Schematic showing the overall architecture of the Antikythera Mechanism in a 2006 model (Freeth et al., 2006). The front and back faces are shown left and right, respectively. A revised model, presented in 2008, shows some small-scale differences on the back dials of the Mechanism (right); in the function of the upper subsidiary dial and the geometry of the main lower dial (Freeth et al., 2008).

Greek names of the Zodiac, and a calendar dial, marked with the names of the Egyptian calendar in Greek. A date pointer shows the date in the Egyptian year. This pointer also served as a representation of the mean position of the Sun in the tropical year. Whether there also was a pointer that displayed the true variable speed of the Sun is still under debate (Wright, 2002a). Furthermore, the front face contains a pointer that shows the position of the Moon on the Zodiac, and also displays the phase of the Moon (see Figure 1.2).

The back face is even more extraordinary than the front. Two large spiraled dials display time relative to astronomical cycles, well known in ancient times. Within these dials are at least two small subsidiary dials. These dials provide in additional information with respect to the large spiraled dials. They also relate abstruse astronomical determinations of time with the calendar of civic society.

Freeth et al. (2008) disclosed the surprising finding that the subsidiary dial in the top spiral-dial represents the Olympiad cycle. It shows the timing of the Olympic Games in ancient Greece, which were called the Panhellenic Games in that time. There is a close link between astronomical time-reckonings and the start of the Olympic Games, since the games started on the Full Moon closest to the summer solstice. This link between the technical astronomical calendars and the everyday calendars that regulated ancient Greek society, yet again emphasizes, what an ingenious and exceptional apparatus the Antikythera Mechanism is.

1.2 In search of lost planets

Even though numerous ancient secrets of the Antikythera Mechanism have been deciphered, there are still many questions and riddles surrounding the mechanism. Who made it? What was it for? What other information did it enclose? And just as fascinating are the implications for our view of the civilization in which it originated, and the speculations on why nothing more advanced succeeded it for such a long period of time.

The research described in this thesis aims to investigate, whether it was possible that the mechanism reproduces the positions of the five known planets. And how such a design would be arranged. One could say we are attempting to redesign the planetary extension for the Antikythera Mechanism, to present the planets of the classical world: Mercury, Venus, Mars, Jupiter and Saturn. Or, as the Greek knew them: Hermes, Aphroditê, Ares, Zeus and Kronos, respectively.

While there is not one direct indication, for any planet related gearing in the Antikythera Mechanism, we wish to forward the hypothesis that it in fact did contain such machinery. There are various strong arguments, why one would expect the planets to be part of the Antikythera Mechanism. The following, are amongst the main arguments used to advocate this stance:

- **The references of Cicero**

  Marcus Tullius Cicero (106 – 43 BC) seems to describe the a device much like the Antikythera Mechanism itself on multiple occasions. Cicero was a Roman statesman, lawyer, political theorist, philosopher, and Roman constitutionalist. He is widely considered one of Rome's greatest orators and prose stylists. In two of his writings, references to mechanisms likely related to the Antikythera Mechanism can be suspected.

  In 79 BC., Cicero went to Rhodes to study under the leading scientist and Stoic philosopher, Posidonius. There, Cicero saw a mechanism, which came to be known as *Posidonius' Orrery* (Keyes, 1928). This mechanism was able to represent the motions of the celestial bodies: *"...the orrery [...] reproduces the same motions of the sun, the moon and the five planets that take place in the heavens every day and night."* As he continuous in his *On the Republic. On the Laws (Book I, Section XIV)*, it seems unambiguously clear that **this mechanism contained planetary gearing for the five planets**.

Secondly, Cicero writes in his book *Tusculan Disputations (Book I, Section XXV)*, about Archimedes. **The latter possesses a globe on which the movements of moon, sun and five wandering stars can be reproduced**: *"For when Archimedes fastened on a globe the movements of moon, sun and five wandering stars, he, just like Plato's God who built the world in the "Timaeus", made one revolution of the sphere control several movements utterly unlike in slowness and speed. Now if in this world of ours phenomena cannot take place without the act of God, neither could Archimedes have reproduced the same movements upon a globe without divine genius"* (King, 1927). Could it be, that this is also a reference to the Antikythera Mechanism?

- **A plausible relation with Archimedes**
  Archimedes of Syracuse lived from around 287 – 212 BC., and was one of the greatest inventors, engineers, mathematicians, astronomers and physicists of the Hellenistic era. The main reason for our interest lies in the fact that he is supposed to have invented a planetarium (King, 1927), and to have written a lost book on astronomical mechanisms (Hultsch, 1878; Dijksterhuis, 1987). In their article, Freeth et al. (2008) reported that **the inscriptions and months on the outer faces of the Antikythera Mechanism are, unexpectedly, of Corinthian origin**. The Corinthian colonies of northwestern Greece or Syracuse in Sicily are leading contenders. Due to the fact that the mechanism is made around 150-100 BC., it is not too far-fetched to suggest a heritage going back to Archimedes.

- **The inscriptions on the instrument**
  The fragmentary inscriptions located on the surviving fragments of the Antikythera Mechanism, **tell of the planets**. For instance, one of the inscription reads *"...τηζ αφρδίτηζ ...,"* which is translated by *"...of Venus ..."* (Freeth et al., 2006; Wright, 2007). Why would the planets be mentioned on the outer plates of the Antikythera Mechanism, if they are not an integral part of the device?

- **The irregular features of Fragment A**
  The large wheel in the largest surviving fragment of the Antikythera Mechanism contains many irregular features, like holes, pins and nuts. According to Wright (2002a, 2007), these features, as well as the actual large size of this wheel, are circumstantial evidence for epicyclic gearing. This sophisticated method of constructing gear trains is **able to reproduce the motions of the known planets, according to the epicycle theories** held by in the Hellenistic era.

- **The sophisticated nature of its gearing**
  The sophisticated nature by which the gear trains of the Antikythera Mech-

> anism are designed, does indicate the advanced level of technological sophistication used in the device. Most notably, the pin-and-slot mechanism, that reproduces the epicycle motion of the Moon. Having devised one epicyclic movement the designer could not have overlooked the possibility of repeating it as many times as he wished. Therefore, **it would almost be illogical if the planets would not be part of the original design**. The elegant sophistication of what survives of the Antikythera Mechanism, and the facility with which an extended reconstruction of it as a planetarium may be devised and made to work, suggests that it is plausible that has been a complete planetarium.

The clues described above, expound the fact that there is sound reason to believe in the existence of a planetary extension for the Antikythera Mechanism in classical times.

1.3 Outline of this thesis

In order to get an unambiguous result in our attempt to redesign the movement of the planets, one needs to speculate about the hypothetical extended architecture of the mechanism. To do this properly, one needs to know more than just the blue prints of the reconstructed devices; one needs to know whether its appropriate considering the known fragments of the mechanism, the technological knowledge of the ancient Greek with respect to gears and gear trains, and the cosmological ideas of that time in ancient Greece.

Therefore, the path towards our goal follows an extensive and thorough road. We start with a retrospect of the excavation and discovery of the fragments of the Antikythera Mechanism in Chapter 2. We discuss the place it took in the scholarly world following its first investigations, during most of the twentieth century. In order to fully appreciate and understand the first reconstructions, we are forced to re-inquire the scientific – and with that especially astronomical – occupations of the classical Greek world.

In Chapter 3, we discus the early astronomical investigations and the relevant philosophical setting, that led towards the scientific revolution of the Hellenistic era. In particular, the origin of the relation between the celestial bodies and their mathematical description. Chapter 4 bestows the astronomical time-reckonings known in ancient Greece, of which numerous are represented in contemporary reconstructions of the Antikythera Mechanism and several are of central importance in developing the planetary extension. The knowledge handled in these two Chapters is crucial in understanding the role of the Antikythera Mechanism in antiquity, and with that grasping the state of technological progress in its era.

In consideration of this last aspect, Chapter 5 forms an integral part of our research. We set forth the different epicycle theories that developed in the Hellenistic era, and show self-made simulations in order to illustrate their internal differences. Comparing these models with the reconstruction of the Antikythera Mechanism places boundary conditions, as well as guidelines, as to which epicycle model could be implemented in the planetary extension of the device.

In Chapter 6, we return to the present day research and investigations of the Antikythera Mechanism. We display the different reconstructions of the device made in last couple of decades, and focus on the extraordinary features that have been ascertained and deciphered over that time. This is our last step in constructing a frame of mind, wherein the design of the planetary extension is imperative to fit.

The blueprint of our extended architecture for the movement of the planets will be composed in Chapter 7. After examining the necessary orbital periods, different gears and possible gear trains, we aim to construct a plausible model for the planetary extension.

Chapter 8 provides a discussion of our work, as well as the accompanying conclusions. It also touches on the different aspects of future work, with respect to this subject, before this thesis concludes in Appendix A.1, containing several expositions of photographs and X-ray images from the surviving Fragments of the Antikythera Mechanism.

Chapter 2

Discovery and investigation of Item 15087

2.1 The Antikythera Youth

Shortly before Easter of 1900, a party of Greek sponge-fishers from the island of Syme near Rhodes in the Dodecanese, left their normal fishing grounds in the Tunisian waters of North Africa and began to sail East, through the channels between Kythera and Crete, towards home (Price, 1974). These channels are amongst the chief shipping routes between the Eastern and the Western Mediterranean. Driven off course they sought shelter near Port Potamo on the almost uninhabited, rocky and barren island of Antikythera. This island in the Western Aegean lies just midway between the two larger islands, splitting the channel between and because of its sandbars, shoals and sudden currents, an infamous dangerous graveyard for shipping, in ancient and modern times (in Figure 2.1 a map of the region is presented).

After the storm, they decided to explore the island's shore and the shallow rock shelf below them in the hope of finding sponges in the unfamiliar territory. Elias Stadiatis, one of the divers in the party, put on a weighted suit and an airtight helmet that was connected by an air hose to a compressor on the boat, and went into the water. Going to a depth of approximately 45 meters, he found to his own amazement, that a great ship lay wrecked on the bottom. A ship with a length of some 50 meters. The real excitement, however, was not so much in the ship itself, but in the treasure that was plainly visible: a pile of bronze and marble statues and other objects made almost unrecognizable through marine deposits.

Stadiatis returned with a piece of one of the bronze statues; a larger-than-life right arm. After that, the party returned to Syme in order to plan a successful trip to the sea bed. Half a year later the sponge-fishers returned as an official Greek recovering mission, with a ship provided by the Greek navy and a official archaeologist to supervise the salvation.

During several runs, taken over the period of nine months, they managed to salvage a wide collection of artifacts. After-wards, these items were taken to the National Archaeological Museum of Athens to be cleaned and reassembled. It was the world's first large-scale underwater archaeological excavation.

They managed to recover a fine bronze head of *the philosopher*, two bronze statuettes, the remains of a group of five or six bronze draped male figures and the famous *Antikythera Youth*; a bronze statue of a nude god or hero, also known as the *Antikythera Ephebe* (Myers, 2006; Fraser, 1928). Although bronze sculptures were common in ancient Greece, only a few have survived. The bronze was often sold as scrap or melted down, to be recast as weaponry. In fact, most of the bronzes known from ancient Greece nowadays have been recovered from shipwrecks (Weinberg et al., 1965).

Unlike the bronze pieces, the marble objects did not survive the 2,000 years under sea that well. Being leprous, blackened and more corroded than the bronzes, they also seem to be less valuable artistically; they all appear to be copies of originals, made for the export trade, early in the first century BC. Other artifacts included bronze fittings for wooden furniture, coins, pottery, an oil lamp and several unidentified artifacts, among which *item 15087*: a shoebox-size lump of bronze with what appeared to be a wooden exterior. But the real discovery of this interesting item would still be a small year away.

Evidence derived from the coins, amphorae (a type of ceramic vases with two handles and a long neck narrower than the body), and other items from the cargo eventually allowed researchers to fix a reasonable date for the shipwreck to 85-60 BC. (Edmunds and Morgan, 2000). This was a time when the glorious civilization of ancient Greece was on the wane, following the Roman conquest of the Greek cities in the First Mithradatic War.

Some scholars have speculated that the ship was carrying part of the loot of the Roman General *Lucius Cornelius Sulla Felix*, or simply *Sulla*, from Athens in 86 BC., and might have been on its way to Italy. A reference by the Greek writer, Lucian, to one of Sulla's ships sinking in the Antikythera region gave rise to this theory (Price, 1974).

The ship itself was built from much older timbre, dating somewhere around 200 ± 45 BC. (Price, 1974).

Coins from Pergamon, a Hellenistic city in what is now Turkey (Figure 2.1), indicated that the ship had made port nearby Antikythera. The style of the amphorae strongly suggested that the ship had called at the island of Rhodes,

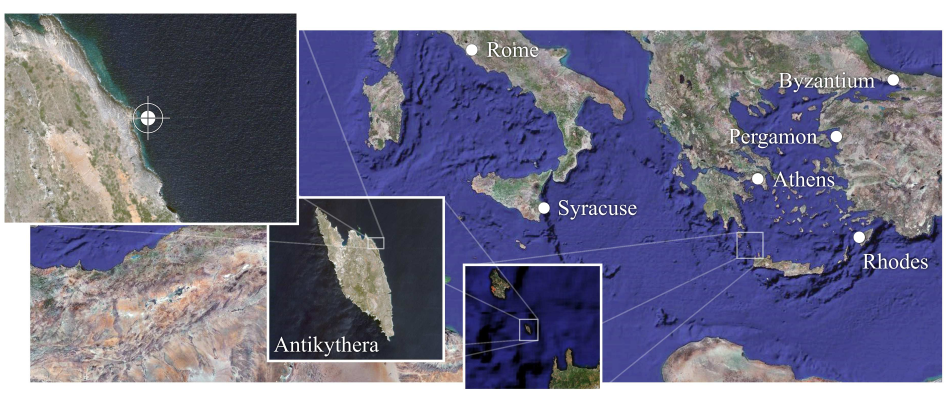


Figure 2.1: Collage of maps of the Eastern Mediterranean. Presented are the location of the shipwreck (top left; according to Price, 1974), the island Antikythera, and the most famous and influential places and regions in classical Greece. The map recounts the great spread of the civilization that now embodies the ancient Greek.

Figure 2.2: Bronze relics from the Antikythera shipwreck. Sub-figure **a** shows the fine bronze head of *the philosopher*, sub-figures **b** shows a pair of bronze feet and sub-figure **d** shows a right hand and arm, and a left hand; both set of limbs are part of the remains of a group of five or six draped male figures. Sub-figure **c** shows the well-known *Antikythera Youth*, also known as the *Antikythera Ephebe* (Myers, 2006; Fraser, 1928). All items are exhibited at the National Archaeological Museum in Athens.

which was known for its wealth and industry at that time. Given the reputed corruption of officials in the provinces of the Roman Empire, it is possible that the ship's cargo had been plundered from Greek temples and villas, during the First Mithradatic War, and was on its way to adorn the houses of aristocrats in Rome. In fact, it was very well possible that the sheer weight of the cargo contributed to the ship's destruction (Weinberg et al., 1965).

2.2 Item 15087

The fragments of the mechanism with which we are concerned, were not remarked upon until nearly eight months after the excavations had been terminated. Where most of the salvaged items were accounted in several dozen newspaper and journal accounts of the flow of minor and major objects from Antikythera to the National Archaeological Museum, there was no report of the existence of these pieces of corroded bronze with their interesting and clear traces of gear wheels and inscriptions; indexed as item 15087.

The first account was published on Friday, May 23, 1902, in the Athens newspaper *To Asty* (No. 4141), six days after the discovery of the inscriptions by a Greek archaeologist named Spuridon Spaïs (Price, 1974). He found them among the bronze pieces which were kept in a caged enclosure to be examined after the restoration of the large bronze statues found in the Antikythera shipwreck.

Staïs noticed that the wooden exterior was split open, probably as a result of exposure to air, and that the artifact inside had fallen into several pieces. Looking closely, Staïs saw some inscriptions in ancient Greek, about two millimeters high, engraved on what looked like a bronze dial. This caused considerable excitement, though its true nature was not understood. Following research revealed precisely cut triangular gear teeth of different sizes. The apparatus looked like some sort of mechanical clock, but this seemed impossible, since scientifically precise gearing wasn't believed to have been widely used until the fourteenth century – fourteen hundred years after the ship went down.

After the discovery of the fragments, item 15087 soon became known as *the Antikythera Mechanism*; the name by which it is still known today. Its first analysis followed two main approaches (Seabrook, 2007). The archaeologists of the National Archaeological Museum, led by J.S. Svoronos, thought that the device must have been some kind of *astrolabe*. This is an Hellenistic astronomical device, which was widely known in Islamic world by the eighth century and in Europe by the twelfth century. They were used to tell the time, and could also determine the latitude with reference to the position of the stars. Muslim sailors often used them, in addition, to calculate prayer times and find the direction to Mecca. Figure 2.3 shows an example of an astrolabe made by M. b. Abi Bakr, Isfahan around 1221 AD. The construction follows the design of al-Biruni from c. 1000 AD.

Other researchers, led by the German philologist Albert Rehm, thought the Mechanism appeared much to complex to be an astrolabe. Rehm suggested that it possibly might have been the legendary sphere of Archimedes, which Cicero had described in the first century BC. as a kind of "mechanical planetarium", capable of reproducing the motions of the Sun, the Moon and the five known planets – Mercury, Venus, Mars, Jupiter and Saturn.

Others even thought that the device must have come from a much later shipwreck; acknowledging the artifact's complexity. This later shipwreck could have

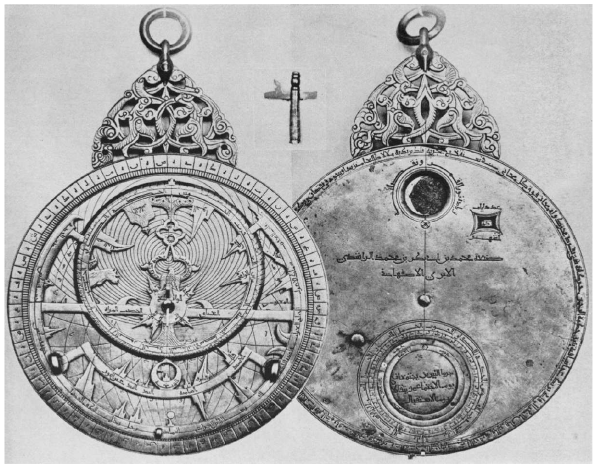


Figure 2.3: Astrolabe containing geared calendar work. This instrument was made by M.b. Abi Bakr, Isfahan in 1221/2 AD. The gearing follows the design follows the gearing reported by al-Biruni c. 1000 AD. Even though it contains features similar to the Antikythera Mechanism, the technology used to make it, and also the manner to use it, is quite dissimilar.

settled on top of the ancient ship, even though the Mechanism had plainly been crushed under the weight of the other cargo of the ancient ship. In the end, it was the astrolabe theory that was most popular until the nineteen-fifties, even though, the technology of these eastern devices is quite dissimilar to the technology of the Antikythera Mechanism, or the western clocks which originated in the fourteenth century.

2.3 Ancient technology

Throughout modern history, scholars have been traditionally reluctant to credit the ancients with technological skill. This has not been different with respect to the early research on the Antikythera Mechanism. Even though there were many known examples of advanced technological mechanisms in ancient times (Price, 1964), scholars tended to focus on the time of Copernicus and Galileo as the time where science and technology began (Price, 1974; Keyser and Irby-Massie, 2002).

The great Greek inventor, scientist, engineer, mathematician and astronomer, Archimedes of Syracuse – already mentioned because of his famous planetarium – is known for many ingenious inventions. One of these inventions was a terrible clawed device, made up out of large hooks; designed and used for lifting fully loaded enemy warships out of sea and smashing them down on the water. Philon of Byzantium invented a spring driven catapult. Heron of Alexandria formulated the basic principles of steam power, he made a mechanical slot machine, a water-powered organ and automatic driven doors (James and Thorpe, 1988). But, he is perhaps best remembered for his mechanical simulations of men and animals, called *automatons*. These devices were cleverly engineered to sing, blow trumpets and dance, among others. And still, even though his book called "Pneumatica" survives til present times, some scholars have dismissed his descriptions as fantasy. They pointed to the lack of textual evidence and the fact that none of these amazing mechanisms had been found (Drachmann, 1963; Seabrook, 2007).

However, is the lack of these mechanisms a real surprise? Keyser and Irby-Massie (2002) observes that the texts that do survive, tend to be the more popular texts. The actual mechanisms probably broke down, were sold as scrap or were recycled. After time the know-how faded, and with the following dissolution of the Roman Empire, the technological knowledge possessed by the ancient Greeks disappeared from the West completely.

The more fundamental underlying question should thus be: if the Greeks did posses this greater technological sophistication than we think they did, why did they not apply it to making more useful things? Why did we not find any evidence for the existence of time and work saving machines? According to Keyser and Irby-Massie (2002), the Greeks had little incentive to invent labor-saving devices, because they owned slaves. In the case of weaponry, the claws of Archimedes are an exception with respect to the cultural resistance to high-tech war machines, since both the Greeks and the Romans valued individual bravery in war more highly.

Another reason for the lack of evidence of ancient technology is mentioned by Marchant (2006), who states that it all depends on what one sees as 'useful.' The Greeks were not interested in accurate time keeping. It was enough to tell the hour of the day, which the water-driven clocks of the time could already do fairly well. They did value knowledge, power and prestige, which explains the various mechanisms driven by hot air or water. But instead of developing, for instance, a steam engine, the devices were used to illustrate philosophical principles. The machines were intended to offer a deeper understanding of cosmic order, and their best technology was used for demonstrating the laws of physics.

A third, and last, reason why we find so little evidence for any grand technological sophistication, might lie in the fact that there metallurgy skills were not suitable yet (Singer et al., 1957a). Greco-Roman metallurgy was a continuation of that of the ancient Near East, and was essentially a phase of the Iron Age wherein copper and bronze were only being slowly displaced by the newcomers; iron and steel. Greeks and Romans added but two fundamentally important discoveries to the knowledge of earlier smiths. First of all, they introduced the production of mercury and its applications to the extraction of gold. Secondly, they discovered the manufacture of the copper-zinc alloy, brass.

Metallurgy remained essentially a charcoal-smelting technique, with all limitations thus implied. Coal is scarce in the Mediterranean region, and its use in metallurgy was first attempted in western and central Europe, by native smiths, in their forges and smelting-furnaces. In the Mediterranean, deforestation had become serious by classical times, so that the prices of timbre and charcoal were rising steadily and ominously. In this still agricultural world, the mines and smelting-sites were very uncommon; there were no true industrial areas in ancient Greece.

So, without any easy access to the necessities for metalworking. And without strong iron and steel, there was no obvious practical application for Greek technology. Therefore, it is easy to believe it never existed at all, and there was no substantial reason for scholars to dismiss the traditional reluctance towards ancient technological skills.

However, in 1958 a new wind began to blow.

2.4 Derek de Solla Price

In 1958, Derek de Solla Price, a fellow at the institute for Advanced Study in Princeton, went to Athens to examine the Antikythera Mechanism. He was born in Britain and trained as a physicist, but switched fields and became the Avalon Professor of the History of Science at Yale. He is often credited as the father of scientometrics; the science of measuring and analyzing science itself. The study of the Mechanism, which incorporates elements of archeology, astronomy, mathematics, philology, classical history and mechanical engineering was ideally suited for a polymath like Price, and it consumed the rest of his life.

Price contrived the idea that the mechanism was some kind of "ancient computer," which could be used to calculate important celestial events in the near or distant future, such as the next full moon, for instance. He was the first who realized that the large encrypted circular bronze plate of one of the fragments was a large dial with calendrical markings indicating months, days and the signs of the Zodiac.

Price postulated the idea that there must have been pointers, to represent the Sun and the Moon and possibly the five planets. These pointers would move around the dial, indicating the position of the heavenly bodies at different times.

In order to prove his theorems, Price went to base his ideas on the fundamental properties of gearing. Gears transmit motion through rotational motion, and by realizing mathematical relationships between toothed gears. Price assumed that the largest gear in the artifact, clearly visible in Fragment A, was tied to the movement of the Sun. If the motion of the Moon was related to the large gear, then the ratio of gears in the gear train must have been designed to match the ancient Greeks' idea about the motion of the Moon. By counting the number of teeth in each gear, one could calculate the gear ratios, and by comparing these ratios to astronomical cycles, the true representation of the gears can be figured out.

"Nothing like this instrument is preserved elsewhere. Nothing comparable to it is known from any ancient scientific text or literary allusion. On the contrary, from all that we know of science and technology in the Hellenistic age we should have felt that such a device could not exist."

– Price (1959)

However, only a small fraction of the gears are visible from the outside of the fragments, and even parts are visible of those outer gears. Therefore, Price and the Greek radiographer C. Karakalos were permitted to make the first X-ray images of the mechanism in 1971. These observations showed – entire or partial – most of the thirty gears inside the fragments. These images, combined with his method for estimating the total number of teeth from partial gear tooth counts, enabled Price to develop a schematic drawing of a hypothetical reconstruction of the internal workings of the mechanism. After several introductory and expounding articles (Price, 1955, 1956, 1959), Price published the major part of his research in a seventy-page article entitled "Gears from the Greeks," in 1974 (Price, 1974). This was a monumental step forward in understanding the Antikythera Mechanism. He writes in his 1959 article published in the *Scientific American*: *"Nothing like this instrument is preserved elsewhere. Nothing comparable to it is known from any ancient scientific text or literary allusion. On the contrary, from all that we know of science and technology in the Hellenistic age we should have felt that such a device could not exist."*

Price's work, though widely reviewed in scholarly journals, did not change the way in which the scientific community viewed the ancient Greek (Charette, 2006). Scholars and historians where still reluctant to rewrite the history of technology to include Price's work – a work that was not on text, like the sound writings of Homer, Sophocles or Horace.

An additional reason could be that Price's work was published at the height of the popularity of "Chariots of the Gods;" a 1968 book by the Swiss writer Erich von Däniken, which stated that highly intelligent aliens had seeded the earth with technology (von Däniken, 1970). With this, Price got associated with U.F.O's, crop circles, the *Piri Reis Map* and a vast variety of pseudo scientific theories. Up until present times, the Antikythera Mechanism is a prominent subject in the works of Von Däniken and his congeners (von Däniken, 2000). For these reasons it is easily remarked, and not even uninstructive, that the Antikythera Mechanism dropped and sank twice, once in the sea, and once in scholarship!

A striking story, associated with this scholarly reluctance, was written down by the exceptional physicist Richard Feynman in 1980 (Feynman and Leighton, 1988). During his visit to the National Archaeological Museum in Athens, he saw the Antikythera Mechanism for the first time. He described it as *"one thing so entirely strange and different that it is nearly impossible."* When he asked the curator to know more about item 15087, he responded: *"Of all the things in the museum, why does he pick out that particular item, what is so special about it?"*

2.5 Present day research

Although his fundamental insights about the device were sound, his work on the Antikythera Mechanism was unfinished when Derek de Solla Price died of a heart attack, in 1983.

Fortunately, his work was picked up by several scientists in the late 90's of the twentieth century. The British clockmaker Michael Wright published, along with a number of associates, several articles in which accomplished great advances in deciphering the Antikythera Mechanism and managed to improve the primary model of Price.

Simultaneously, a number of astronomers, archaeologists, computer engineers and physicists, from mainly Britain, Greece and the United States, who had all published about the mechanism, collaborated to form the Antikythera Mechanism Research Project (AMRP). They aim to use the most up to date computer-based imaging techniques to reconstruct a more precise model, and managed thus far to publish several ground breaking articles about the topic (Freeth et al., 2006, 2008).

2.6 Historical implications

Even if the Antikythera fragments had been no more than a few small bronze wheels and gears of uncertain function, they would constitute an historical relic of enormous interest and importance for the history of technology and our knowledge of ancient technological knowledge.

In a 2006 *Nature* article, François Charette writes the following: *"During renovation work in a northern Italian plazzo, an enigmatic artifact comes to light, dated to the late fifteenth century. After intensive analysis, it is identified as a complex steam engine – constructed 200 years before French inventor Denis Papin's pioneering experiments, and 300 years before the Industrial Revolution. Our view of the technical achievements of the Renaissance is completely changed. The reverberations are felt far beyond just scholarly circles"* (Charette, 2006).

Of course, this did not happen. However, the find of the Antikythera Mechanism, and the continuing discoveries that are made around the device, are forcing a comparable rethink of the technology of classical antiquity. Or, like Price claimed that the Mechanism *"requires us to completely rethink our attitudes toward ancient Greek technology"* (Price, 1974).

CHAPTER 3

The rise of Greek physical conception

3.1 Astronomy at the dawn of the Greek era

In order to fully appreciate what an exceptional accomplishment it was for the Greek engineers of the Hellenistic era, to construct the Antikythera Mechanism, it is essential to investigate the early Greek scientific enterprises. In this Chapter, we will discuss the early astronomical investigations and the relevant philosophical setting, that led towards the scientific revolution of the Hellenistic era.

Homer and Hesiod

The oldest surviving works of Greek literature are the *Iliad* and *Odyssey* of Homer, which were put into writing from probably around the end of the eighth century BC. Only a little younger is Hesiod's *Works and days*, which dates from around 650 BC. During this time, the Greeks were just emerging from their dark age. Literacy had been gained, then lost in the convulsion of the twelfth century BC., then regained at this dawn of the Classical Greek.

Historians turn to Homer and Hesiod for insight into the Greek societies around 700 BC., as well as Greek's economic life, their social organization, and their religious practices of that time. Likewise, these works can be used to inquire of Homer and Hesiod just what the Greeks knew of astronomy.

In the *Iliad*, a few stars and constellations are mentioned by name: the Pleiades, the Hyades, Orion and the Bear; which in later time became known as Ursa Major. Homer also mentions the Dog Star, Arcturus and the constellation Boötes. Apparently, it was known that different stars are conspicuous at different times of year.

For the early Greeks, astronomy was a practical matter, a means to fix the times for performing agricultural operations or religious rites, at a period when they had no adequate calendar. This is apparent from the poem *Works and days*, where can be read: *"When the Pleiades, daughters of Atlas, rise, begin reaping, and when they set, begin ploughing."* That is to say, the rising of the star-group of the Pleiades just before dawn, which was about the middle of May at Heriod's time and location, is the signal for the start of harvesting. Likewise, the cosmical setting of the Pleiades, at the end of October in Greece, warns that is time for the autumn sowing and ploughing (Walker, 1996).

This agricultural calendar relied primarily on the rising and setting of popular stars, like Sirius and Arcturus, or groups of stars, like Orion, the Pleiades and the Hyades. There thus was some sort of precursory knowledge of the Zodiac, or at least the movement it follows along the night sky (see Figure 3.2). Secondly, they relied on the summer and winter solstices, which the Greek called *turnings*, from the word *tropai.* At these times, the Sun reached its northernmost or southernmost point on the horizon, and turned to move in the opposite direction.

Most of the knowledge of the celestial bodies was thus being used for practical requirements: being used to tell the time of the year, to know when to sow, to predict the coming of the seasons (Evans, 1998). But furthermore, they were already used to navigate. In the *Iliad*, Homer mentions that Ursa Major *"turn about in a fixed place,"* and *"is never plunged in the wash of the ocean."* Even *Odysseus* keeps the Bear on his left, in order to sail to the east."

Early Babylonian astronomy

In Babylonian astronomy of about 700 BC., many features can be recognized that seem similar to the Greek astronomy of that time. However, in many ways Babylonian astronomy was further advanced.

Babylonian astronomical documents, like the *MUL.APIN* clay tablet[1] (Walker, 1996), or the so-called *Circular Astrolabe* (Evans, 1998), contain evidence of two complementary processes; one in which theories, capable of representing and predicting observations, were created; the other involved the use of those theories to predict phenomena (North, 1994). These phenomena are of course what is usually encountered in surviving tablets, and the first process has to be reconstructed from it. It required a set of skills, to create theories which represented and predicted observations, which could be exercised by people well drilled in routine procedures, but they need have had little understanding of these procedures.

Figure 3.1: The astronomical compendium MUL.APIN. The tablet, only 8.4 *cm* high, is a masterpiece of miniature cuneiform writing. About 500 BC.

It was from this tradition of looking at the sky, and recording every noteworthy observation, that the Greek inherited a vast quantity of centuries of observations out of the Southern regions of Mesopotamia.

In the case of ancient Greek cultures and civilizations, they could observe very accurately very large portions of their own night sky once the art of processing large

[1]The MUL.APIN is a compendium, in the form of an extraordinary clay tablet, that deals with many diverse aspects of Babylonian astronomy. The text lists the names of 66 stars and constellations and gives a number of indications, such as rising, setting and culmination dates, that help to map out the basic structure of the Babylonian star map. The tablet dates back to about 500 BC., and is only 8.4 *cm* high.

sets of observational had been learned from their eastern sources, but this happened at a relatively late date. The most significant influence took effect only in the second century BC., and the man deserving most of the credit for this change was Hipparchus. By then, however, the Greeks had developed a geometrical method of their own, that was to assume an extraordinary importance in subsequent history. They modelled the heavens on a sphere, with stars, planets and circles on it, and they learned to explain the simple daily and annual movements in terms of the rotation of the celestial sphere.

3.2 Early astronomy in classical Greece

In the fourth century BC., it was Aristotle who established a tradition of collecting together the opinions of previous thinkers and subjecting them to criticism, as vigorously as if they were still alive. Some of his collected material goes back to the sixth century BC., but like other collectors he was largely dependant on unreliable intermediaries. This is particularly true of the four earliest philosophical thinkers of note: Thales, Anaximander, Anaximenes and Pythagoras.

Thales

Thales (c. 624 – c. 546 BC) was born in the city of Miletus. This was an ancient Greek Ionian city on the western coast of Asia Minor, near the mouth of the Maeander River. Aristotle considers him to be the founder of Ionian natural philosophy. Stories were told by Aristotle of his intense practicality; for example, he used his astronomical knowledge to predict an oversupply in the olive crop. He then got a monopoly on the presses, and made a fortune. On the other hand, he was presented as a visionary, so engrossed in a study of the heavens that he fell down a well, unable to see what was in front of him – according to Plato.

Thales is supposed to have predicted an eclipse of the Sun that took place during a battle between the Lydians and the Persians, and that is now usually set at May 28, 585 BC. This is a much debated story, but can almost certainly be disregarded except as a symbol of myth-making at the time of Aristotle.

A pupil of Aristotle, Eudemus of Rhodes, was assigned with astronomy and mathematics, and tells the story that Thales brought his astronomical knowledge to Greece, after a visit to Egypt. Others have argued that Thales got his knowledge from the Babylonians.

Anaximander & Anaximenes

Anaximander and Anaximenes argued cosmological views that, as North (1994) put it, are almost as similar as their names. The second was possibly the pupil of the first, around the time of the fall of Sardis (546 BC). Like Thales, both came from the Miletus, the southernmost of the great Ionian cities of Asia Minor – at the western extreme of modern Turkey.

Anaximander (c. 610 – c. 546 BC) belonged to the Milesian school and learned the teachings of his master Thales. He succeeded him and became the second master of that school where he counted – besides Anaximenes – Pythagoras amongst his pupils. Anaximenes of Miletus (c. 585 – c. 525 BC) was from the latter half of the sixth century, a younger contemporary of Anaximander, whose pupil and friend he is said to have been.

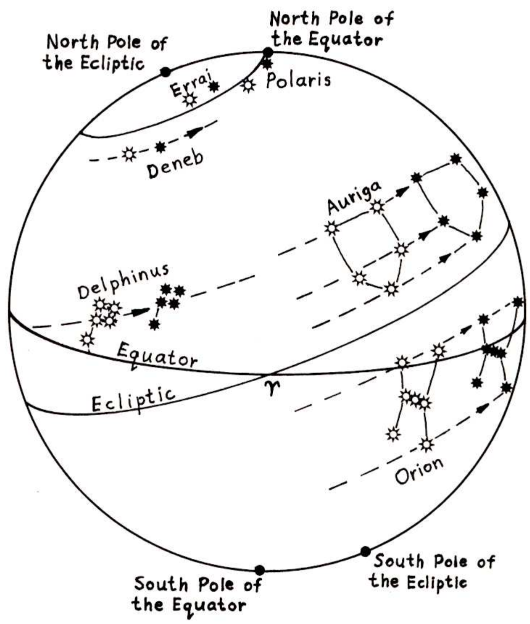


Figure 3.2: The stars, as seen as on a globe, from the outside. The sphere of stars, rotates about the poles of the ecliptic for west to east. Shown are the celestial equator and the ecliptic, as well as their poles, and the effects of precession; the open symbols show the position of the stars 2,000 years ago, the solid symbols are the present day positions. The point indicated by ϒ is the definition of the vernal equinox.

Anaximander is set to have made a map of the inhabited world. The infinite universe, he said, was to be the source of an infinity of worlds, of which ours was but one. These others worlds separated off and gathered their parts together by their rotatory motions. This analogy with vortex motion has perhaps more to do with the observations of cooking vessels than of slings. But even though the origin of his line of thought was probably very different, not entirely dissimilar theories were being advanced in Newton's seventeenth century; masses of fire and air were supposedly sent outwards and became the stars. The Earth was some sort of floating circular disc, and the Sun and the Moon were ring-shaped bodies, surrounded by air.

Strange though these ideas now seem, we catch glimpses of a type of scientific reasoning that is by no means trivial.

When Anaximenes elaborates on Anaximander's ideas, and argues that air is the primeval infinite substance, from which bodies are produced by condensation and rarefaction, he produces logical arguments based on everyday experiments. Again he introduces rotatory motion as the key to understanding how the heavenly bodies may be formed out of air and water.

These attempts at creating a *physics of creation* are characteristic in much of classical Greek thought, and show a significant difference, in their engagement towards science and astronomy, with respect to the Babylonians. Where the Babylonians were exceptional bookkeepers of the heavenly occurrences and phenomena related with those, they were, as far as we now, never truly occupied with the questions why things happened. The early Greek philosophers – who were just as much astronomers and cosmologist – were exceptionally important for the later history of cosmological thought (Dreyer, 1953).

Pythagoras

Pythagoras of Samos was born between 580 and 572 BC., and died between 500 and 490 BC. He was an Ionian Greek mathematician and founder of the religious movement called Pythagoreanism. He is often revered as a great mathematician, mystic and scientist; however some have questioned the scope of his contributions to mathematics and natural philosophy. Herodotus referred to him as *"the most able philosopher among the Greeks."*

Despite his large religious following, nothing Pythagoras wrote has come down to present times, still it seems that he took the ideas of Anaximander and Anaximenes one step further. He claimed that all things were numbers. Pythagoras seems to have been convinced that everything, from opinions, opportunities, injustices or the most distant stars is rooted in arithmetic, and has a corresponding place in the structure if the Universe as a whole. Whether or not this mystical belief can be defended, there has been scarcely any period in history since that time when it has not had important repercussions on scientific thought.

Aristotle tells of a geometrical model of the Universe, proposed by the Pythagoreans, involving a central fire around which the celestial bodies move in circles. This central fire was not the Sun, although the Earth was certainly of the character of a planet to it. To account for Lunar eclipses, the Pythagoreans postulated a counter Earth (North, 1994).

It was about the this time also, that the Zodiac was introduced into Greece from Babylonian sources. Almost simultaneously, the recording of the solstices, which had long been under observation, was being given greater attention, in order to improve either the civil calendar or the calendrical scheme into which astronomical observations were fitted.

Simultaneously, models were made that tried to explain the motion of the Sun, Moon and planets around the Zodiac. Figures 3.2 illustrate the motion of the celestial objects.

Slowly but surely a characteristically physical style of Greek thinking was beginning to develop, and was soon to begin to yield important results.

3.3 The celestial spheres

Greek astronomy in the fifth century BC., like that of the Near East, was intertwined with the study of meteorological phenomena like the clouds, winds, thunder and lightning, shooting stars and the rainbow. This component remained, with an astrological underpinning, until modern times. But, far more important in the long term, were the seeds of the geometrical methods that early Greek procedures contained (North, 1994).

The discovery that the Earth is a sphere, was traditionally assigned to Parmenides of Elea , in 515 BC; he is also said to have discovered that the Moon is illuminated by the Sun. A generation later, Empedocles and Anaxagoras seem to have given a correct qualitative account of the reason for Solar eclipses, namely the obscuration of the Sun's face by the intervening Moon.

Astronomy was spread very thinly through the period leading to the first great age of mathematical advance; the fourth century, which began with the remarkable planetary scheme of Eudoxus, and ended with the first extant treatises of spherical astronomy, those by Autolycus and Euclid. Small but important developments

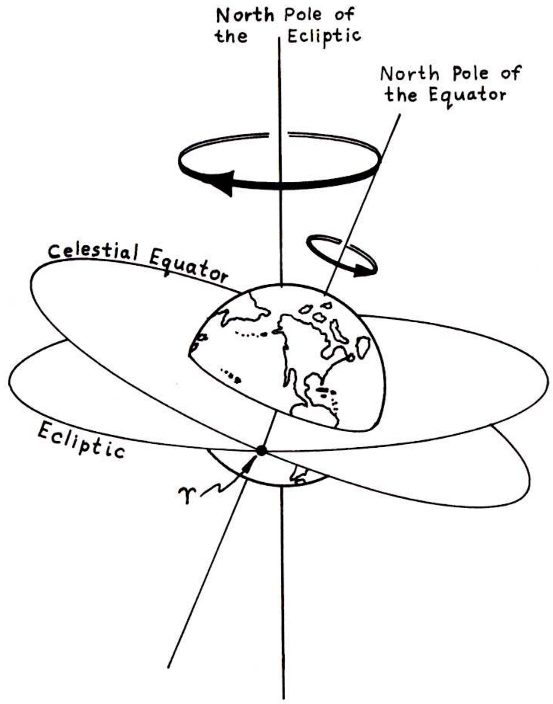


Figure 3.3: Alternate view of the celestial equator, the equator and precession. The Earth's axis rotates about the poles of the ecliptic from east to west. Consequently, the vernal equinox ♈ also moves to the west.

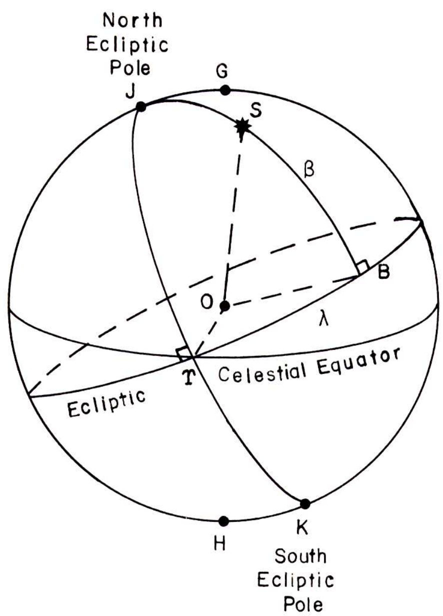


Figure 3.4: Illustration of the ecliptic coordinates. The celestial longitude of a heavenly object is represented by λ. The celestial latitude of an object is represented by β.

were taking place however.

The change that took place in Babylon, from the listing of stars by reference to the Zodiacal constellations to a system of elliptical longitudes, had occurred around 500 BC. Reckonings as we do now, from a zero-point where the ecliptic and the equator meet, did not come for another six centuries. Figure 3.3 illustrates the vernal equinox, celestial equator and the ecliptic, which Ptolemy introduced in the western world for his definition of the tropical year. Figure 3.4 represents the accompanying manner for measuring angles in longitude λ and latitude β.

In stead of defining a vernal equinox, the Babylonians had reckoned from the zero-points of each Zodiacal sign, measuring in each from 0 to 30 degrees. Still, the Greeks of the fifth century BC., had nothing comparable.

Eudoxus

The discovery of the sphericity of the Earth, and of the advantages of describing the heavens as spherical, captured the imagination of the time of Plato and Aristotle, in the fourth century BC. One man in particular was captured by this concepts; Eudoxus of Cnidus.

Eudoxus (c. 400 – c. 347 BC) was born in Cnidus, an ancient Spartan city on a peninsula at the south-west corner of Asia Minor. On a first visit to Athens, he studied with Plato, who was approximately thirty years older. He later visited Egypt, to study with the priests at Heliopolis, before he returned to Asia Minor. Back home, he founded a school at Cyzicus, rivalling Plato's Academy in Athens. Through him, and his many students, the influence of the school was considerable, though, his work was not fully appreciated throughout history. His planetary theory, however, attracted much attention from the beginning (North, 1994).

No writings of Eudoxus have survived, but his system can be pieced together from the writing of Aristotle and Simplicius – the latter was a Platonist, born in the early sixth century AD., and he who wrote influential commentaries on Aristotle's work, but he was no mathematician. Eudoxus' system is built up from concentric

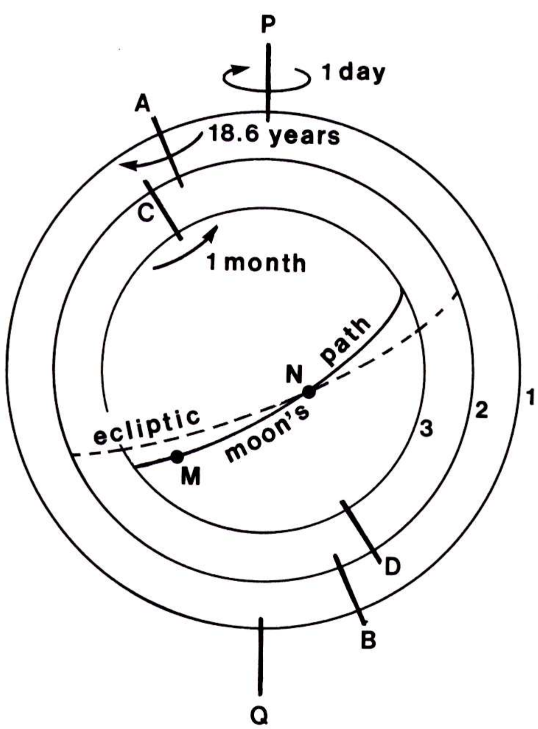


Figure 3.5: Eudoxus' model for the motion of the Moon. Sphere 1 produces the daily motion. Sphere produces the motion of the nodes of the Moon's orbit, and explains why eclipses do not occur always in the same Zodiac sign; it is a representation of the draconic period (see Section 4.1). Sphere 3 produces the monthly motion around the path inclined 5° to the ecliptic. A similar model was applied to the motion of the Sun (Evans, 1998).

spheres, centred on the Earth. It was the theoretical Universe of a mathematician, where all the spheres lie inside one another, but their different sizes are ignored (Walker, 1996).

To describe the Sun, one needed at least two spheres, one for the rapid daily rotation, the other for the Sun's annual motion in a contrary direction. The second sphere then needed to be pivoted around the poles of the ecliptic circle. The Moon could have been roughly described along the same lines. Still, Eudoxus added a third sphere, for both the Sun and the Moon. To what account he did this, is still debated. Figure 3.5 illustrates the model for the Moon, constructed by the spheres of Eudoxus.

It was in his explanations of the *direct* and *retrograde* motions of the planet, that Eudoxus' pivoted spheres came into their own. In the fourth century BC., it was well known that the planets did not wander through the sky with a constant velocity, or even in a constant longitudinal direction. The superior planets – Mars, Jupiter and Saturn – were known to follow retrograde paths across the night sky.

Retrograde motion is motion in the opposite direction. In the case of celestial bodies, such motion may be real, defined by the inherent rotation or orbit of the body, or apparent, as seen in the skies from Earth. In a heliocentric model it is easy to explain why this phenomena is observed from the Earth. Figure 3.6 illustrates the apparent location of a superior planet, and why it seems to move backwards, when the Earth catches up with it. Figure 3.7 displays a composite image, made with observations of the motions of the planets over seventeen years. It clearly shows the apparent loops in the orbits of all the five planets.

Eudoxus was able to show in his model, how a point on the spheres could describe a figure-of-eight; a *hippopede*. In approximating the qualitative motion of the planets in this way. With this, their seemingly erratic motions had been reduced to a physical law.

Eudoxus provided with the makings of a powerful geometrical model for the planetary motions, exhibiting the motions with a total of twenty-six spheres. And even though, the model suffers from severe limitations, since it is a purely qualitative theory and the spheres are unable to accommodate the real motions of the planets. It is the first geometrical model trying to explain the motions of the celestial objects. Eudoxus produced a very remarkable planetary theory, based entirely on spherical motions. In terms of its predictive power, this theory cannot beat comparison with the Babylonian arithmetical schemes, but it was in many ways

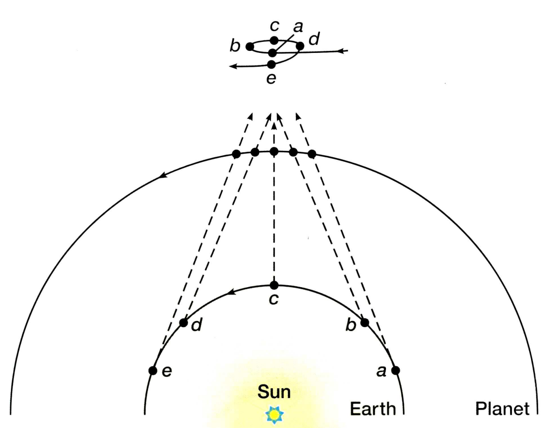


Figure 3.6: Illustration of the apparent retrograde motion of the superior planets across the night sky. Shown are five different times of the year, and the according locations of the Earth and the superior planet. The arrows and projections indicate how these planetary motions translate into the apparent loops as seen on Earth.

Figure 3.7: A composite image, made out of observations of the motions of Mercury, Venus, Mars, Jupiter and Saturn over seventeen years. It clearly shows the apparent loops in their orbits.

more important. First of all, it showed the later world the great power of geometrical methods. Secondly, by an accident of history – its adoption by Aristotle – it was for two thousand years instrumental in shaping philosophical views on the general form of the Universe.

3.4 The Greek philosophy of spheres

While we are mainly interested in the birth of Greek astronomy, and therefore focus on the early astronomical proceedings, it is very important to acknowledge the influence of two of the most influential philosophers of ancient Greece, with respect to this subject.

Plato and the motion of the planets

Plato (c. 427 – c. 348 BC) was born in Athens. He is generally considered, together with his mentor, Socrates, and his student, Aristotle, to have laid the foundations of Western philosophy

It is often said, that is was Plato, who explained how the observed motions of the planets may be explained, in order of uniform and orderly motions of the heavens. While the views of this great philosopher are of much interest, his influence on mathematics and astronomy is easily exaggerated. His contribution mainly stemmed from his concern that, both astronomy and mathematics, were part of the education of the ruling class and the ordinary citizens. Though, as a propagandist, his influence is still a force to be reckoned with.

In his book *the Timaeus*, Plato describes the creation of the Universe by the Demiurge out of the four basic elements. He also describes a relatively simple model for planetary motion, made with hoops. This shows clearly that he already has a real model for the motion of the heavenly objects (North, 1994). However, for his most complex representation of the motions of the heavens. We have to turn to one of his earlier books. In the tenth book, of one of his finest works, *the Republic*, Plato introduces a myth, told with much use of poetic imagery by Socrates. It is the story of *Er*; a man killed in battle, whose soul visits the land of the dead, to return after his miraculous revival. Socrates tells how Er's soul went to a certain magic place, where he saw the mechanism of the entire planetary system; with nested bowls and hoops – of *whorls*, turning around a spindle of steel, and each carrying a planet. This rested in turn on the knees of Necessity, the daily rotation as well as the planetary motions being thus taken care of. The whorls were turned by the daughters of Necessity; the Fates, and on each spindle, a Siren sang a single note, so that together they made a harmonious sound.

Even though, there is no mention of a counter earth, an equator or of the Zodiac, the myth of Er suggests very strongly that physical models of the Earth were being made, and not merely described. To describe such a Universe as Er's, one would surely have introduced complete spherical shells, and whatever the whorls were, they would have been open-topped, to allow one to see into the workings of the cosmos.

Aristotelian cosmology

Aristotle was by far, the most influential ancient philosopher of the sciences. He was born in Stagira in 385 BC., and died in 322 BC. on the island Euboea. His family was a privileged one; his grandfather had served as a personal physician to the grandfather of Alexander the Great, and Alexander was in turn a pupil of Aristotle. He studied under Plato in Athens, until the latter's death in 348 BC., and after moving to Mycia, Lesbos and Macedonia, he returned to Athens where he founded his own school of philosophy, *the Lyceum*. His very extensive writings are highly systematic and coherent, and cover a large part of human knowledge (Lindberg, 1992).

The most important single source for Aristotle's cosmology, his *De caelo* ('On the heavens'), was an early treatise, and does not contain all of what in his work was most influential. It does not, for instance, have the theory of the *Unmoved Mover*, for which we must consult his *physics*. This entity, at the outermost part of the Universe, was taken to be the source of all movement of the spheres within it.

As mentioned, Aristotle writes in a semi-historical way, collecting together the opinions of previous thinkers and subjecting them to serious criticism. The longest chapter in *De caelo* concerns the celestial sphere and the spherical Earth at its centre. He mentions the theories of the Pythagoreans, and of an unnamed school, according to which the Earth rotates at the centre of the Universe. He dismisses that idea, as well as the idea of an orbital motion of the Earth. Both of these we now of course accept. Aristotle sees to have been persuaded by Eudoxus' theory that, if accepted, they would imply that the stars are subject to 'deviations and turnings', and that we experience those. Eudoxus had unwittingly scored a hit for the fixed-Earth doctrine. If alive, he might have pointed out that if the stars are at great distances, the argument fails.

Aristotle offers various arguments for the spherical nature of Earth and the Universe (Lindberg, 1992; North, 1994). The Universe he conceives is to be built layer over layer over a spherical Earth. Only circular motion is capable of endless repetition without a reversal of direction, and rotatory motion is prior to linear because what is eternal, or at least could have always existed, is prior, or potentially prior, to what is not. Circular motions are for Aristotle a distinguishing characteristic of perfection, and therefore, the heavens acquire a special place in any discussion of perfection. In fact, the heavens are so special, that according to Aristotle, they are not made up out of the four elements found on Earth: earth, air, fire and water; they are made out of a fifth element, or *essence*, called the *quintessence* – also known as the ether.

For the technicalities of Aristotle's planetary system we must turn to his *Metaphysics*. There he seems to be accepting the theory of Callipus, who proposed a modified theory of Eudoxus', where thirty-three spheres describe the motions of heaven. However, he notices that if all the spheres put together, are to account for what we see, then for each of the planetary bodies, there must be other 'unrolling' spheres to counteract the effects of the spheres above them, that do not belong to the planet in question.

Aristotle's is thus a mechanical view of the Universe, of spherical shells with various functions, only some carrying planets. Motions were no longer being postulated as though they were items in a geometry book, nor were they justified in terms of Platonic intelligences, but rather in terms of physics of motion, a physics of cause and effect. With one exception; the first sphere of all, the first heaven, transmits its circular movement to all lower spheres. But what moves this sphere? There are many theological interpretations of this prime mover, whose activity is the highest form of something divine (Keyser and Irby-Massie, 2002). Still, no unambiguous can not be given to this question.

It is important to recognize that both Plato and Aristotle, had a major impact in introducing a philosophy of perfect spherical motions. One which is held on to through vast periods of history, till long after their time.

Chapter 4

Astronomical periods known in ancient Greece

4.1 Lunar cycles

It was about the time of Pythagoras, in the fifth century BC., that the Zodiac was introduced into Greece from Babylonian sources. Almost simultaneously, the recording of the solstices, which had long been under observation, was being given greater attention, in order to improve either the civil calendar or the calendrical scheme into which astronomical observations were fitted.

During this period, also the motion of the Moon was studied, and various Lunar cycles were distinguished (Neugebauer, 1975a,b,c; North, 1994; Evans, 1998).

Synodic month

The time it takes for a Moon to make one revolution around the Earth, with respect to the Sun became known as the *synodic month*, roughly 29.5306 days. With a Full Moon, the Sun, Earth, and Moon are on one line, with the Earth in the middle. With a New Moon, the Sun, Moon and Earth are on one line, with the Moon in the middle. This period is responsible for, and describes, the waxing and waning of the Moon. The image at the top left of Figure 4.1 illustrates the Synodic period.

Sidereal month

A sidereal period, is the time it takes a celestial body, to reach the same place in the sky with respect to the background stars. A *sidereal month* is therefore defined as the time it takes for the Moon to reach the same place in the sky with respect to the celestial sphere; a period of 27.3217 days.

Tropical month

The mean time required for the Moon to travel from one equinoctial point, all the way around the Zodiac, and return to the same point is called a *tropical month.* It

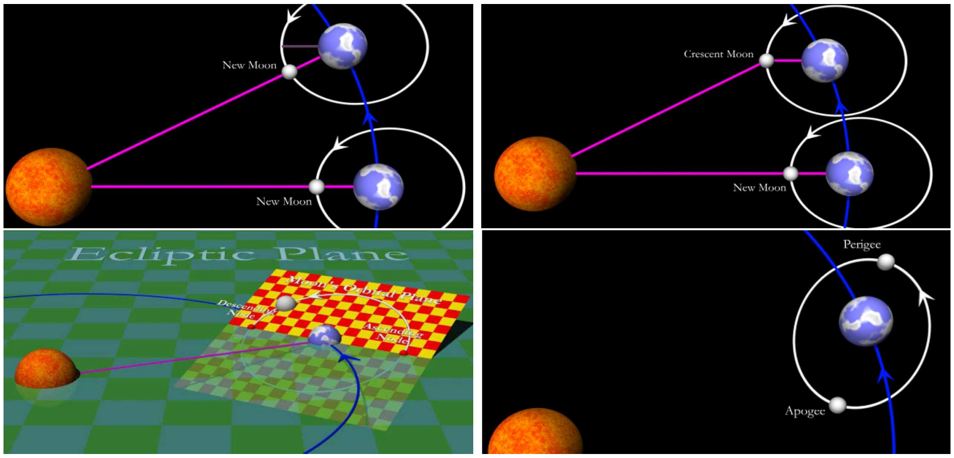


Figure 4.1: Series of panels, illustrating the different astronomical Lunar periods. The image top left, illustrates the succeeding positions of the Sun, Earth and Moon in one synodic period. The second panel, top right, illustrates the different positions of the Sun, Earth and Moon in one sidereal, as well as one tropical period. The panel at the bottom left illustrates the tilted Lunar plane and the ecliptic, thus representing the draconic month. Finally, the fourth panel at the bottom right, illustrates the positions of the Lunar apsides, which are necessary to appreciate the anomalistic month.

is about 27.3216 days, slightly shorter than the sidereal period because the vernal point precesses.

The image at the top right of Figure 4.1 illustrates both the sidereal and the tropical month.

Draconic month

The plane of the Moon's orbit is slightly tilted with respect to the plane of the orbit of the Sun, which is known as the *ecliptic*. Therefore, the Moon can wander approximately 5 degrees away from the Sun's path. The line of intersection between the plane of the Moon's orbit and the ecliptic defines two points on the celestial sphere: the *ascending node*, which is the location where the Moon's path crosses the ecliptic as the Moon moves into the northern hemisphere, and the *descending node*, which is the location where the Moon's path crosses the ecliptic as the Moon moves into the southern hemisphere.

The time it takes for the Moon to make one revolution around the Earth, from ascending node to ascending node, is known as the *draconic month* or the *nodical month*, and its duration is about 27.2122 days.

In turn, the plane of the orbit of the Moon rotates also around the Earth. It takes the plane about 18.6 years to make one sidereal revolution around the Earth.

The image at the bottom left of Figure 4.1 illustrates the draconic month.

Anomalistic month

The ancient Greeks already noticed the varying angular sizes of the full Moon. The angular sizes are smallest or largest when the Moon is at one of the extremes of the ellipse. These two extremes – or *apsides* – of the ellipse are called the *perigee* and the *apogee* (see Figure 5.6). The point of closest approach is called the perigee;

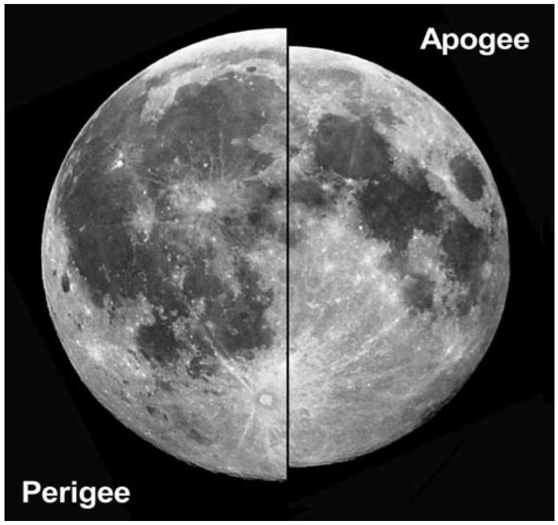


Figure 4.2: The difference in angular size of the Moon near perigee and apogee (Greco, 2005)

this is the point where the Moon has its largest velocity. The point of farthest excursion is called the apogee; and the is the point where the Moon has its smallest velocity.

Now, the time it takes for the Moon to travel from its perigee all the way around its orbit and return to its perigee is called the anomalistic month, and takes a period of 27.5546 days.

The anomalistic month is illustrated in the bottom right image of Figure 4.1.

Because of the tidal effect of the sun, the orbit of the Moon precesses, and thus, its apsides are not kept at a constant orientation with respect to the stars. The result is that the perigee and apogee make one revolution of a cycle in just under nine years.

The phenomena of varying angular Full Moon sizes, is described by the *Full Moon Cycle*; this is the period it takes for the Full Moon to go from the largest angular size and shrink, until it eventually starts growing again and the same maximum diameter is achieved.

The angular size of the Moon depends on how close the Moon is to the Earth in its elliptical orbit. It is the same period the Sun takes – as seen from the Earth – to complete an orbit relative to the Moon's perigee. Likewise, it can be seen as the beat period of the synodic and the anomalistic month (Freeth et al., 2008).

Most of these periods were also known by the Babylonians. And since they describe such rudimentary processes, there is no known discoverer. They are, however, extremely important in describing different astronomical phenomena. For example, it is the synodic month that describes the different shapes of the Moon, and it is the draconic month, that is used to predict eclipses; if the ecliptic and the plane of the Moon were not tilted, there would be an eclipse every month, at Full Moon. Because the Moon wanders around its 5 degree flight, this is not the case. This means that there can only be an eclipse when the Moon is sufficiently close to its node. This results in a Solar eclipse, when the Moon is at a node, and it is a New Moon, and it results in a Lunar eclipse when the Moon is at a node and it is a Full Moon.

4.2 Calendar cycles

The Metonic Cycle

Scientific astronomy in Greece began in the fifth century BC., when on the hill of the Pnyx, in Athens, the summer solstice of 432 BC. was observed by the astronomers Meton and Euctemon. This is the oldest known Greek observation (North, 1994; Evans, 1998). Whether or not it is correct to speak of a school of astronomy founded by the two Athenians, both seem to have collaborated in proposing a regular calendar cycle of nineteen years; the so-called Metonic Cycle:

$$\textit{19 Tropical Years} = \textit{235 Synodic Months} = \textit{6,940 days}.$$

The same cycle was discovered earlier by the Babylonians. Whether Meton's result represents a borrowing from Babylonian or an independent discovery, is unknown. However, Euctemon is known to have devised a *parapegma*, of star calendar, which listed chronologically the appearances and disappearances of the most prominent stars in the course of a year. The Babylonians seem to have used another parapegma then the Athenians. These parapegma were needed to calculate the lengths of the months.

According to the Greek astronomer and mathematician Geminus, out of the 235 months, 110 were 'hollow' months of 29 days, and 125 were 'full' months of 30 days. To account for these differences, the astronomers in both Greece and Babylon made rules of intercalation; the insertion of extra days. The parapegmata were used to calibrate the Metonic cycle with the civil calendars.

The Callippic Cycle

A century after Meton and Euctemon, Callippus of Cnidus, a student of Eudoxus, improved the Metonic Cycle by taking four periods, which sum up to 76 years, and removing 1 day:

$$\textit{76 Topical Years} = \textit{940 Synodic Months} = \textit{27,759 days}.$$

The Callippic Cycle was used yet later by Hipparchus and Ptolemy in another modified and improved form:

$$\textit{304 Topical Years} = \textit{3,760 Synodic Months} = \textit{111,035 days}.$$

It is clear however, that Hipparchus' refinement was never practically employed. The simpler cycles of 19 and 76 years were for most purpose enough, and the Callippic Cycle eventually became enshrined in the Easter Computus of the Christian Church, where it remains in use to this day.

4.3 Eclipse predicting cycles

The Saros Cycle

Because the position of the perigee of the Lunar orbit is not constant, and because of the regression of the its nodes (see Section 4.1), the circumstances of eclipses do not repeat from one year to the next. But we can form a longer period after which the circumstances do more or less repeat.

Suppose, a Lunar eclipse occurs on a certain day. Then, after a whole number of synodic months nave elapsed, and after a whole number of draconic months have elapsed, and after a whole number of anomalistic months have occurred, the circumstances will be perfect once again; the Moon will be full again, it will have returned to the same node, and it will again be at the same distance from the perigee as before.

This Lunar cycle is known as the *Saros cycle*, and occurs after the following number of Lunar months:

$$223\ \textit{synodic} = 242\ \textit{draconic} = 239\ \textit{anomalistic months},$$

which in turn is roughly equal to 6,585 1/3 days, or 18.029 years.

Although the 18-year eclipse cycle is already attested in Babylonian material, the name Saros is of modern, probably seventeenth century origin (Evans, 1998).

The Exeligmos

Since the Saros cycle is contains 6,585 1/3 days, we can form a period three times longer, which will contain a whole number of days. Such a period was called the *Exeligmos* by the Greek:

$$669\ \textit{synodic} = 726\ \textit{draconic} = 717\ \textit{anomalistic months},$$

which in turn is roughly equal to 19,756 days, or 54.087 years.

After one Exeligmos, not only the same circumstances of the Lunar eclipse reoccur, it even takes place at about the same time of day.

Chapter 5

Epicycle theories of the Hellenistic era

In order to construct sound hypotheses about the possibility, or presence of any geared planets inside the Antikythera Mechanism, it is important to know which theories they are most likely to apply to. Therefore, this chapter forms an integral part of the research described in this thesis. It deals with the theories of deferents and epicycles, of which the first arose in around the third century BC.

When Alexander the Great died in Babylon in 323 BC., his vast empire was divided into a number of independent realms. These regions were ruled by the senior officers of the late Alexander. The last of these smaller remains came under the sway of Rome in 31 BC. By that time, the other parts had already become provinces of the Roman empire (Kenny, 1998).

The intermediate centuries, in which Greek civilization flourished throughout all the lands around the Eastern Mediterranean, became known as the Hellenistic era.

In this period, Greek colonists came into contact with widely different systems of thought. In Bactria, at the far eastern end of the former Empire of Alexander, Greek philosophy encountered the religion of Buddha. In Persia Greeks encountered the already ancient religion of Zarathustra. And in Palestine, they met the Jews.

The largest realm was that of the Macedonian general *Ptolemy I Soter*, and his descendants, in modern day Egypt and Libya. Here, the new city of Alexandria was built, whose citizens were drawn from every part of the Greek world. The founded a magnificent and well-catalogued library, which became the envy of the world.

A series of brilliant mathematicians and scientists in Alexandria competed with, and in time surpassed, the scholars in the Academy and the Lyceum who, in Athens, carried on the work of their founders Plato and Aristotle. It was a flourishing time, in which a true intellectual revolution triggered the birth of a wide variety of different aspects of science. Among which, the further exploration of mathematical models, able to describe the motions of heaven.

5.1 The early deferent-and-epicycle system

It is in the early days of the Hellenistic age, that the first true mathematical descriptions for the planetary motions arise. Though they are of uncertain origin, most studies point to one man.

The Epicycles of Apollonius

Apollonius of Perge (c. 262 – c. 190 BC) grew up in an ancient Greek city in southern Asia Minor, where he lived in the second half of the third century BC. This was at the start of the Hellenistic era. It is debated whether he studied long with the pupils of Euclid, but he was certainly one of the greatest of Greek mathematicians in antiquity, to be compared perhaps only to Archimedes (Osborne, 1983; North, 1994). He did for the geometry of conic sections what Euclid had done for elementary geometry. Those methods proved to be enormously important for astronomy, especially in the later century of Kepler, Newton and Halley – who all studied Apollonius' text closely.

Even though, Apollonius is known for measuring the distance between the Earth and the Moon, and he is said to have made tables of the Sun and the Moon, he is best known in an astronomical context for his theorem on planetary motions. According to Ptolemy (c. 140 AD.), Apollonius found a relationship between the velocity of a planet moving on an epicycle round the deferent cycle, and the 'irregular' direction and retrograde motions of the planet (Neugebauer, 1959).

In the period between Callippus (c. 330 BC) and Apollonius two models arose; the *eccentric* and the *epicyclic* model. These models represented a major deviation from the divine and perfect spherical model of Aristotle, and are required to fit the models to the observations. In the eccentric model, the planet – or other celestial body – is supposed to rotate with a steady eastward motion on the circumference of a circle placed eccentrically to the Earth. In the epicyclic model, the body rotates uniformly about the centre of a small circle called the *epicycle*, which in turn rotates eastwards about a larger circle, centered on the Earth, called the *deferent*. It is obvious that both models will produce a variation in the distance of the body, and it easy to show that both will also, under suitable assumptions – which include the rotation of the eccentric around the Earth – yield retrograde motion of the planets. The two models are in fact fully equivalent in the mathematical sense (Hanson, 1960; Walker, 1996). In fact, it was Apollonius who proved this in classical times (Neugebauer, 1959). It can be shown in a relative simple scheme (see Figure 5.3).

As stated, little is known about the genesis of these two models; it is imaginable that the astronomers noticed that a displacement of the spheres of Aristotle resulted in a better model, and perhaps it was the Aristotelian philosophy of perfect spherical motions, that nourished the epicycle theory (Pedersen, 1974). Nevertheless, this first epicycle theory became known as Apollonius' model (Evans, 1998).

Apollonius' deferent-and-epicycle model is illustrated in figure 5.1. The figure lies in the plane of the ecliptic, and is observed from the ecliptic north pole. The *deferent circle* is centered on the Earth O. Along this circle, point K moves eastward at constant speed. A second sphere; the *epicycle*, is centered on the moving point K. The celestial body – planet, Sun or Moon – moves on point P, also at a constant speed.

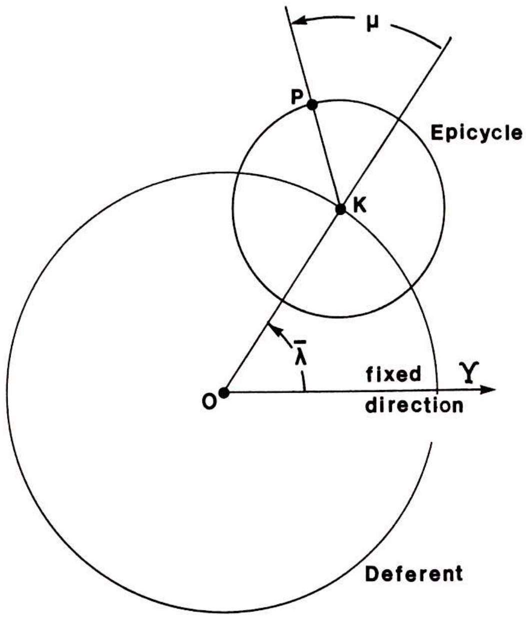


Figure 5.1: Apollonius' epicycle-and-deferent model. The Earth is located at O, the celestial object moves around its epicycle at P, the direction of the vernal equinox (see Figure 3.3) is marked by ϒ (Evans, 1998).

The motion of K around the deferent is designed to represent the mean motion of the celestial object around the ecliptic, K must therefore complete one revolution in one tropical period. The angular distance between K and the vernal equinox ϒ, is called the *mean longitude*, denoted by $\bar{\lambda}$. Thus, $\bar{\lambda}$ increases by 360° in one tropical period.

The motion of P around the epicycle is designed to reproduce the retrograde motion. The location of P on the epicycle is defined by the *epicyclic anomaly*, μ, which increases by 360° in one synodic period.

Figure 5.2 shows a more detailed representation of the deferent-and-epicycle model, including most of the terminology and notation used in Apollonius' model. The point π of the epicycle, which is nearest the Earth, is called the *perigee of the epicycle*. The point a, farthest from the Earth, is called the *apogee of the epicycle*. The object's *actual longitude* at any moment is denoted by λ. A retrograde motion can seem to appear, depending on the orbital velocities of $\bar{\lambda}$ and ν, when the object is at π, for then the motion of P on the epicycle is westward in opposite direction with respect to the motion of K on the deferent; the object then appears to be backing up. Figure 5.4 illustrates the apparent motion of P on its epicycle, and on its deferent, while it travels through the heavens.

When the two motions are put together, the resulting motion shows a series of loops in the case of the superior planets. Between each retrograde loop and the next, the object makes a complete trip around the ecliptic, plus a bit more, which is the resultant of the motion of both the Earth and the celestial object in question.

The Sun

The epicyclic model of Apollonius' describes one of the first theories that accounts for the existence of the Solar anomaly. The Sun, $\odot$, moves on an epicycle, while

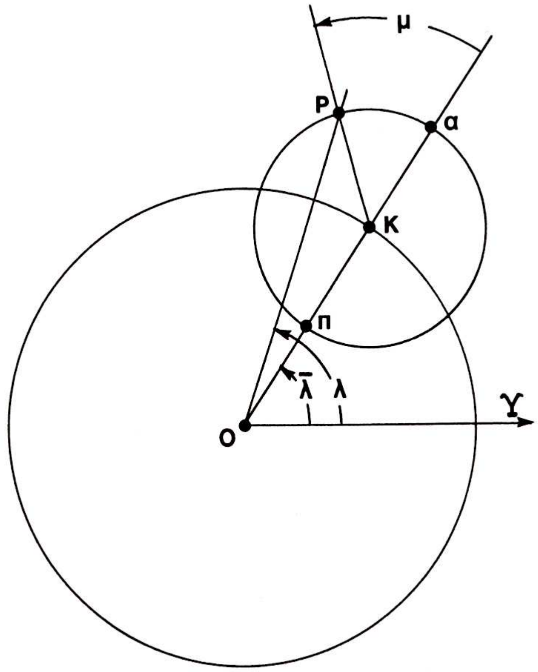


Figure 5.2: Terminology and notation used in Apollonius' deferent-and-epicycle model.

Points labeled in the Figure:
O is the Earth
K is the centre of the epicycle
π is the perigee of the epicycle
a is the apogee of the epicycle
P is the celestial object
ϒ is the vernal equinox

Angles of circles:
$\bar{\lambda}$ is the mean longitude
μ is the epicyclic anomaly
λ is the longitude of the object

(Evans, 1998)

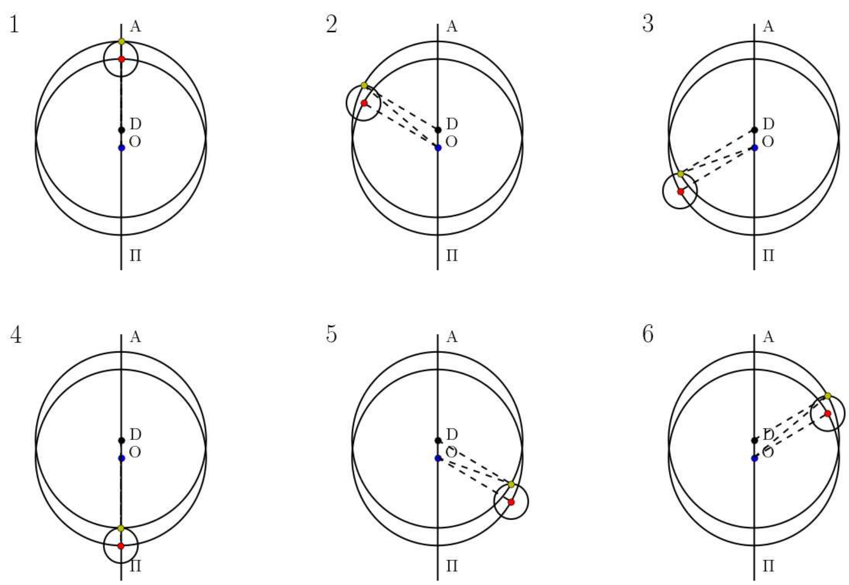


Figure 5.3: Relation between the mean Sun and the true Sun in one tropical year, as well as an illustration of the fact that the eccentric model is mathematically identical to the epicycle model. The blue dot represents the Earth, the yellow dot represents the Sun, the back dot represents the centre of the eccentric sphere, and the red dot represents the centre of the Solar epicycle.

the centre K of that epicycle follows the deferent, around the Earth. In the case of the Sun, the location K is usually referred to as the *mean Sun*, $\bar{\odot}$, and the actual position of the Sun on the epicycle is referred to as the *true Sun*. Figure 5.3 illustrates the Sun on its revolution through one tropical year, with the location of both the mean Sun, red dot, and the true Sun, yellow dot.

Both the revolution of the mean Sun, $\bar{\odot}$, around the Earth, O, as the revolution of the Sun, $\odot$, around its epicycle are completed in one year. Thus, the angles of the longitude of the mean Sun, $\bar{\lambda}_{\odot}$ and the Solar anomaly $\mu_{\odot}$ are always equal.

It is unclear whether Apollonius used his model to represent the motions of the Moon. According to Ptolemy, it was Hipparchus who made two models, predicting the Moon's orbit around the Earth (Pedersen, 1974). However, these two models were analogous to the eccentric and the epicycle model, and it is argued by both Neugebauer (1959, 1983) and Pedersen (1974), that it could very well have been Apollonius who already modelled the motion of the Moon.

The Moon

Looking at the epicycle model of the Moon, we see a model that is quite similar to that of the Sun. The Moon rotates on an epicycle at the rate of the anomalistic month. In turn, the epicycle moves on the deferent at the rate of the sidereal month (Pedersen, 1974; Freeth et al., 2006).

Inferior planets

The inferior planets Mercury and Venus have the same tropical period as the Sun. The move alternately ahead and behind the Sun, but they always remain its close companions. This relation translates in the fact that the direction from the Earth to the mean Sun always coincides with the direction from the Earth to the epicycle's center:

$$\textit{Inferior planet: } \bar{\lambda}_p = \bar{\lambda}_{\odot}. \tag{5.1}$$

In Figure 5.5, this relation is illustrated; O, K and $\bar{\odot}$ all lie in one line. The relation also explains why an inferior planet has limited elongations from the mean Sun.

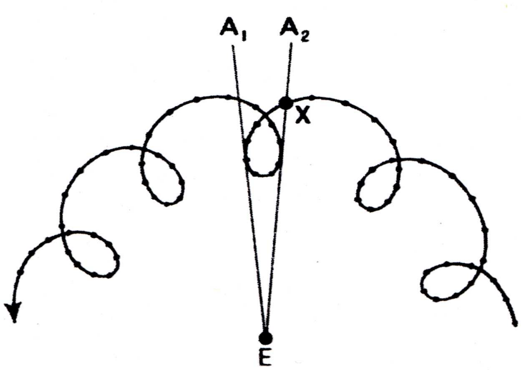


Figure 5.4: Illustration of the resulting epicycle motion for a superior planet, as described by the models of Apollonius, and as seen from the Earth E. The planet moves from point X, anticlockwise to line A1, then clockwise back to line A2, before following its way anticlockwise to line A1.

Superior planets

The superior planets Mars, Jupiter and Saturn, move retrograde when the Earth moves between the planet and the Sun. The speed at which they rotate on their deferent is the same as the orbital times in the present heliocentric model, so, for instance, Mars takes 1.88 years to make one evolution on its deferent. Furthermore, the speed at which they circle on their epicycle is 1 year; equal to the speed at which the Sun rotates the Earth.

Figure 5.6 represents the motion of a superior planet, along with the mean Sun, $\bar{\odot}$, around the Earth. The fact, that the period of one revolution of both the Sun as well as point P takes 1 year, around respectively the Earth and the epicycle, is realized by the fact that the lines from K to P, and from the Earth to the Sun always remain parallel. Thus KP is parallel to $Obar\odot$:

$$KP \,||\, O\bar{\odot}. \tag{5.2}$$

From Figure 5.6, we can deduce a relation between the planet's mean longitude, $\bar{\lambda}_p$, and epicyclic anomaly, μ_p, and the longitude of the mean Sun, $\bar{\lambda}_{\odot}$. First, note that the three angles with vertex at O satisfy the relation $\bar{\lambda}_p + KO\bar{\odot} = \bar{\lambda}_{\odot}$. But since $O\bar{\odot}$ is parallel to KP, angle $KO\bar{\odot}$ has to be equal to μ_p, so we can write:

$$\textit{Superior planet: } \bar{\lambda}_p + \mu_p = \bar{\lambda}_{\odot}. \tag{5.3}$$

In words: the planet's mean longitude plus its epicyclic anomaly equals the longitude of the mean Sun. This equation reflects the period relation for a superior planet: number of tropical cycles elapsed + number of synodic cycles elapsed = number of years elapsed.

Successes and failures of the model

Apollonius' model provides a simple explanation of retrograde motion that is consistent with the principle of Aristotelian physics, that celestial bodies must move on circles at uniform speed.

There are other successes: according to the model, Mars is closest to the Earth during retrograde motion (Evans, 1998). This is in agreement with the observed

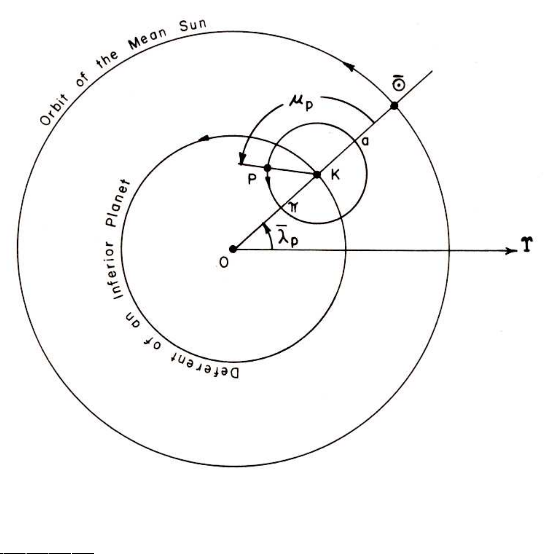


Figure 5.5: Relation between the mean Sun and an inferior planet: $\bar{\lambda}_p = \bar{\lambda}_{\odot}$ (Evans, 1998).

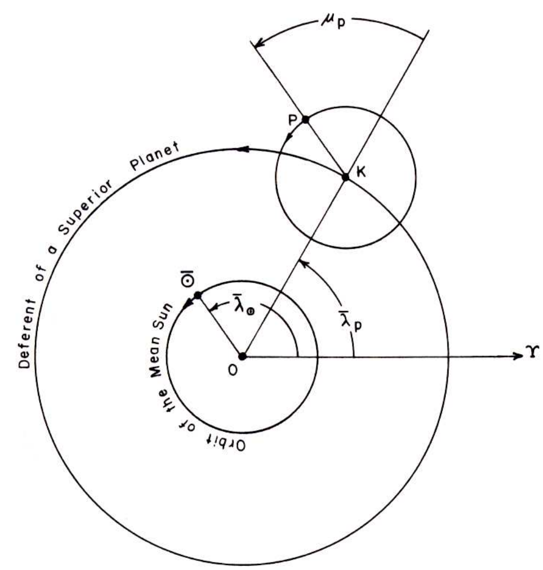


Figure 5.6: Relation between the mean Sun and a superior planet: $\bar{\lambda}_p + \mu_p = \bar{\lambda}_\odot$ (Evans, 1998).

brightness of Mars during retrograde motion. Apollonius' model thus represents an improvement over the concentric spheres of Eudoxus (see Section 3.3).

However, the model is still not capable of predicting the real motions of the planets accurately. The model simply has no numerical predictive power.

5.2 Hipparchus and the intermediate models

Hipparchus of Nicaea (c. 190 – c. 120 BC) is known for his major contributions to ancient and even present astronomy. The discovery of the precession of the equinoxes (see Figures 3.2 and 3.3) is generally attributed to Hipparchus, though the difference between the sidereal and tropical year (see Section 4.1) was already known to Aristarchus of Samos.

According to Ptolemy's brief summary in the *Almagest*, Hipparchus made notable contributions to to the theories of the Sun and the Moon. However, he did not give a theory of the planets, but only rearranged the observations in a way that it showed the inconsistencies of the model, with respect to the hypotheses of the mathematicians (Evans, 1998). He saw, for instance, that the modelled retrograde motions of Mars were not similar to the observed motions. The models of his predecessors described retrograde motions that were identical in shape and duration, Hipparchus noticed that these retrograde motions varied with almost every occurrences.

According to Ptolemy, one of Hipparchus' main contributions was a demonstration that the zero-eccentricity of Apollonius' model was inconsistent with the motions of the planets. Still, Hipparchus' predecessors could hardly have been unaware of this fact.

While Eudoxus and Apollonius saw their job as merely giving a physically plausible, geometrical explanation of retrograde motion, Hipparchus insisted on a planetary theory that could also explain the Zodiacal inequalities. And so, in the period between Apollonius and Ptolemy, Greek astronomers investigated planetary theories that modelled the motions of the celestial bodies with both moving eccentric deferents, and epicycles.

Hipparchus improved Apollonius' model by determination of the Lunar eccentricity and apogee position from three Lunar eclipses. From the angles formed in the three positions with the Earth and with the theoretical centre of the eccentric deferent, Hipparchus calculated the radius of the deferent, as well as the direction of the centre of the deferent (Walker, 1996).

With this observation, Hipparchus must also have noticed the libration of the Moon, and with that, severe indications that the Moon is spherical (Neugebauer, 1975a).

5.3 The Ptolemaic models

The astronomer, mathematician, astrologer and geographer Ptolemy was born around 100 AD., and died about seventy years later. His name *Ptolemaeus* showed that he was an Egyptian descended from Greek, or at least had Hellenized ancestors. His first name *Claudius*, shows that he held Roman citizenship. Beyond these simple facts, virtually nothing is known about a personal sort.

Ptolemy's extensive writings suggest that he was engaged in assembling an encyclopedia of applied mathematics. Of works on mechanics, only the titles are known. Much of his *Optics* and *Planetary Hypotheses* can be pieced together from Greek of Arabic versions. Some minor works on projection, called *Analemma* and *Planisphere*, as well as the monumental *Geography* survive in Greek, as does his great treatise on astronomy, in which we are interested, the *Almagest* (Toomer, 1998).

The title of this, his finest work, is itself an interesting indicator of cultural movements. It began in Greek, entitled as *Mathematike Syntaxis*; which can be translated as *Mathematical Compilation* or *Mathematical Treatise*, and soon became *The Greatest Compilation*. When the Arabs translated it in the ninth century, only the word greatest was kept, but this is an approximation to the Greek word *megiste*, so that it now became *al-majiste*. From there to the latin *Almagesti* or *Almagestum*, in the twelfth century, and thence to our *Almagest*, were small steps.

This work in thirteen books begins with a short statement of reasons for holding to a largely Aristotelian philosophy – but one that shows the influence of the Stoics, too. However, soon he turns to careful discussion of the theories of his predecessors – amongst which the works Hipparchus – and his own well-studied scientific and philosophical ideas (Pedersen, 1974; Evans, 1998).

Ptolemy's theory of longitudes

Figure 5.7 illustrates the planetary model according to Ptolemy for Venus, Mars, Jupiter and Saturn. Much like the theories proposed by Hipparchus and later astronomers, the deferent circle is not centered on the Earth O. Therefore the deferent is equal to the eccentric, which is centered on C.

The line through O and C cuts the eccentric at the apogee of the eccentric A, and at the perigee of the eccentric π. The line through A and π is therefore called the line of apsides. The angle marked with A is the longitude the apogee of the eccentric. This longitude is different for every planet.

The real difference with previous theories, and that what was perhaps the most important personal contribution to planetary theory by Ptolemy, is the fact that K, the centre of the epicycle does not move with a uniform motion around O, or C, but around a third point E; the centre of uniform motion known as the *equant point*. That is, an observer located at E, would see K travel through the sky with a uniform motion; so with equal angles at equal times.

In Ptolemaic astronomy, $CE = CO$, so the that the equant and the Earth are equidistant with respect to the centre of the circle C. If R is the radius of the deferent, the ratio CO/R, which is thus equal to CE/R, is called the *eccentricity*, denoted by e.

Ptolemy's introduction of the equant point into planetary theory means that the point K must physically speed up and slow down. Just like an elliptic orbit, K travels slowly at the apogee, and most rapidly at the perigee. Needles to say, this is bending the rules of Aristotle's physics, where uniform speeds and concentric spheres are at the foundation of his astronomic philosophy (see Section 3.3). However, the rules governing the variation in speed is very simple, since the angular motion appears uniform from E.

Line OZ is parallel to the line EX. The point X rotates around O and E in the same period as Z, though at a uniform velocity. Therefore, the line EX is called the zero-degree reference line for angles measured at the equant. This signifies that the mean longitude $\bar{\lambda}$ increases at a uniform rate.

The planet P moves uniformly on the epicycle in the same way as K does on the eccentric, counterclockwise when viewed from the north pole of the ecliptic. The position of the planet on the epicycle is specified by angle $\bar{\mu}$, referred to as the *mean epicyclic anomaly*. Since P moves with a uniform speed on its epicycle, this means that $\bar{\mu}$ increases uniformly.

As Evans (1998) expresses, often, one reads complaints by popular writers on the history of astronomy that the theory of Ptolemy was complicated, unnatural or arbitrary. However, the planets are as simple as the planets allow. The deferent, with its eternal revolution from west to east, produces the steady progress in longitude associated with a planet's tropical revolution. The epicycle accounts for the second inequality, which is manifested most spectacular in the planet's

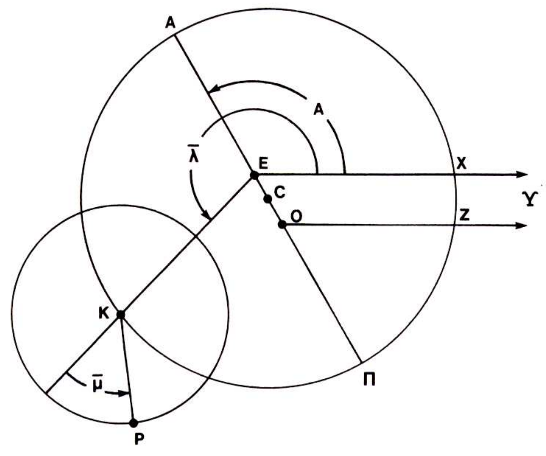


Figure 5.7: Ptolemaic model of planetary theory of longitudes. The Earth is at O, and the centre of the deferent is at C. The point around which the epicycle centre K moves, is located at the equant point E. (Evans, 1998).

retrograde motion. But the planet also has a Zodiacal inequality, i.e. that it does not move through the Zodiac at a uniform speed. The combination of equant and off-centre deferent is Ptolemy's manner for dealing with this inequality. It is important to understand how these features are forced on the model by the planets themselves.

The Sun and the Moon

In Ptolemy's theories, there is very little difference in describing the Sun's motion, compared to the model of Apollonius. It also contains a deferent without eccentricity – thus centered on the earth, on which the mean Sun $\bar{\odot}$ rotates, while forming the centre of the epicycle whereon the true Sun $\odot$ follows its uniform motion eastwards. However, the theory of the Moon did undergo some adjustments (Pedersen, 1974).

It was Hipparchus who measured the parameters of the Moon more precisely, and made the first alterations. Ptolemy took this one step further, and placed the Moon on a rotating deferent. Figure 5.8 shows a series of simulations concerning two revolutions of the Moon around the Earth, according to Ptolemy's model with rotating deferent and epicycle. The series starts with the conditions for a Solar eclipse. The red line represents the crossing of the Lunar orbital plane with the ecliptic. The true Moon (green dot) and the true Sun (yellow dot) are on one line with the Earth (blue dot). The purple dot represents the mean Sun, the red dot the centre of the deferent and the cyan dot the mean Moon.

The small frame at the left bottom of each sub-figure shows the Moon as a white dot, where seen from the Earth. The yellow dot of the Sun drifts through this frame when it is at the same approximate position in the sky. The bottom right frame of each sub-figure shows the different corresponding faces of the Moon; thus related to the positions of the Sun and the Moon.

Concerning the planets

In Section 5.1, we examined the connection between the Sun and the inferior and superior planets for Apollonius' model. In the case of an inferior planet, the centre of the epicycle lies on the line of sight from the Earth to the mean Sun. In the case of a superior planet, the line of the planet to the centre of its epicycle remains parallel to the line of sight from the Earth to the Sun.

Actually, the relationship for inferior planets only holds if the planet's orbit has no eccentricity. This would mean for Ptolemy's model that the equant and the centre of the deferent coincide with the Earth. Since this is not always the case, it is necessary to restate the relations more precisely.

Figure 5.9 illustrates the connection between the mean Sun and the inferior planet Venus. The mean Sun $\bar{\odot}$ travels at uniform speed around a circle centered on the Earth O. The planet P travels on an epicycle whose centre K travels on an eccentric deferent, which his centered on C, and the equant is located at E. Now, in Ptolemy's theory of longitudes EK remains parallel to $O\bar{\odot}$:

$$EK \parallel O\bar{\odot}. \tag{5.4}$$

In other words: the line between K and the centre of its uniform motion, remains parallel to $O\bar{\odot}$, which in that sense is similar to Apollonius' model, where the the line of sight between K and its centre of motion is only shifted onto $O\bar{\odot}$.

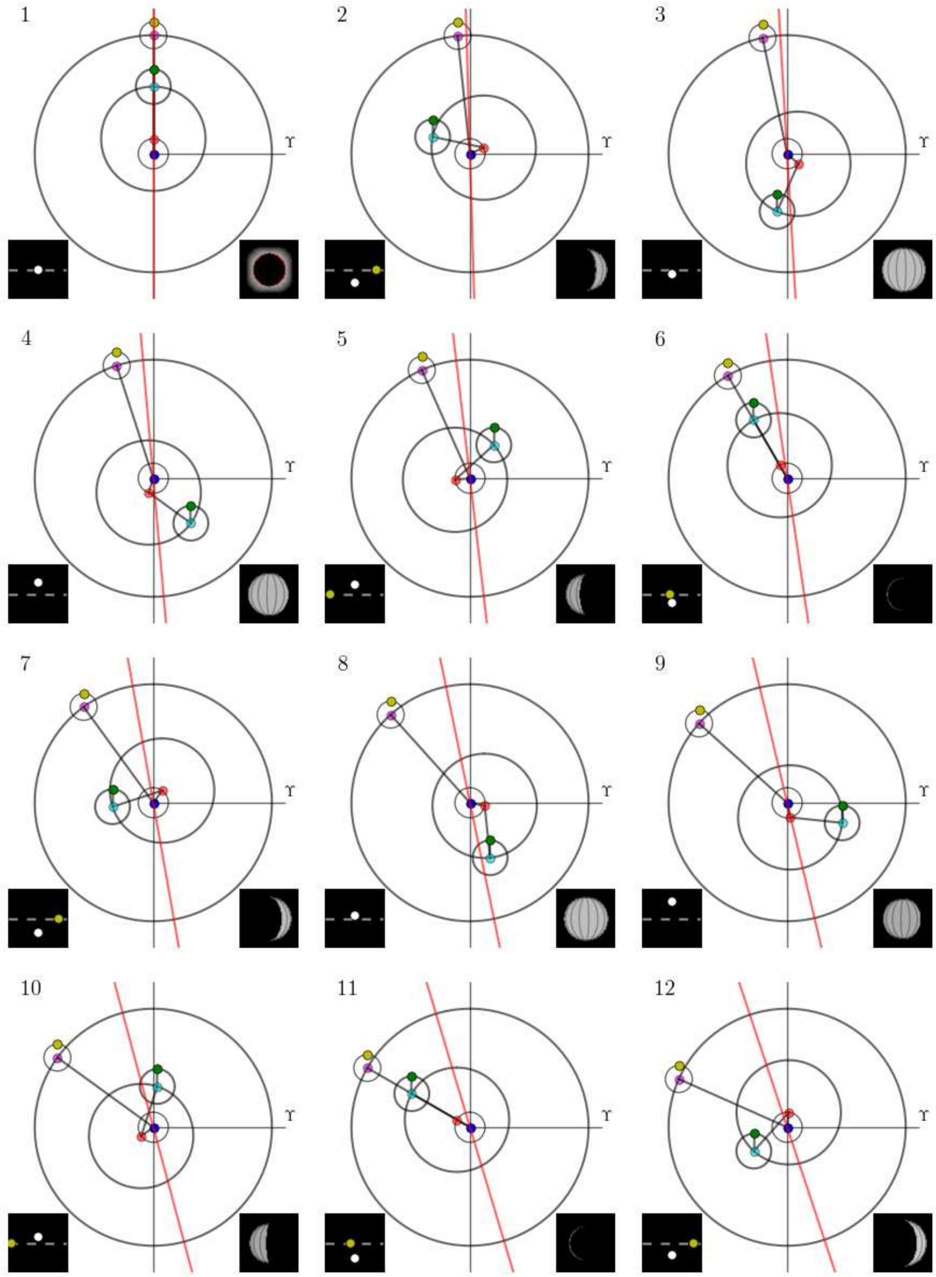


Figure 5.8: Series of panels displaying two revolutions of the Moon, according to Ptolemy's model with rotating deferent and epicycle; starting with the conditions for a Solar eclipse. The blue dot represents the Earth, the purple dot the mean Sun, the yellow dot the true Sun, the red dot the centre of the deferent, the cyan dot the mean Moon and the green dot the true Moon. The red line represents the crossing of the Lunar orbit with the ecliptic. With respect to this Lunar plane, the frame at the left bottom of each sub-figure shows the Moon as well as the Sun as seen from the Earth. The bottom right frame of each sub-figure shows the different corresponding faces of the Moon.

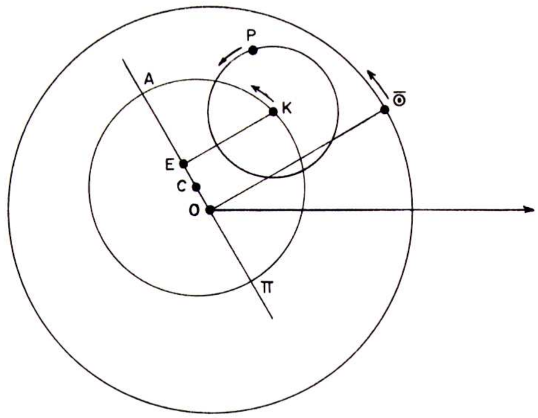


Figure 5.9: Relation between Venus and the mean Sun, according to Ptolemy. EK is parallel to $O\bar{\odot}$ (Evans, 1998).

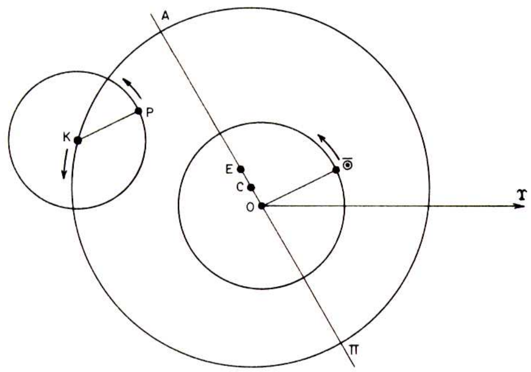


Figure 5.10: Relation between superior planets and the mean Sun, according to Ptolemy. KP is parallel to $O\bar{\odot}$ (Evans, 1998).

It must be noted that Ptolemy introduced a model of Mercury, containing two perigees in one revolution. This model, unfortunately, is based on several erroneous measurements (Pedersen, 1974).

Figure 5.10 illustrates the connection between the mean Sun and a superior planet. The radius of the epicycle remains parallel to the line of sight from the Earth to the mean Sun, like in Apollonius' model KP remains parallel to $O\bar{\odot}$:

$$KP \mid\mid O\bar{\odot}. \tag{5.5}$$

Ptolemy himself states in the *Almagest*, that it will still be the case that when the planet is in opposition to the mean Sun, KP will point directly at the Earth. However, since E and C do not in general coincide, the centre of the retrograde arc will not correspond exactly to the mean Sun position.

The peculiar role of the mean Sun in the ancient planetary theory provided a clue that the Sun deserved a more important role in their world picture. However, it was not until many centuries later that anyone saw the consequences clearly. It is true that several astronomers proposed a heliocentric cosmology, but both on observational – there was no observed parallax of the stars – and philosophical grounds, this idea was dismissed, time after time.

5.4 Successors of Ptolemy

According to one school of thought in the history of astronomy, minor imperfections in the original Ptolemaic system were discovered through observations accumulated over time. More levels of epicycles (circles within circles) were added to the models, to match more accurately the observed planetary motions. The multiplication of epicycles is believed to have led to a nearly unworkable system by the sixteenth century. Copernicus created his heliocentric system in order to simplify the Ptolemaic astronomy of his day, and he succeeded in drastically reducing the number of 'circles,' a term which included both epicycles and (eccentric) deferents (Stimson, 1917).

Nevertheless, Ptolemy's epicycle model was able to represent the orbits of the planets very accurately. Barbour (2001) describes in his book, how Ptolemy's model represents a first order approach of an the ellipse described by the first two laws of Johannes Kepler. An ellipse is equal to a circle in first order. The Earth and the equant are the two foci of the ellipse, and the uniform motion about the equant, is Kepler's second law to first order. That is, the Ptolemaic system was, in many respects, closer to our modern descriptions of the heavens than was the Copernican, which eliminated the equant and off-centre equant.

This, as well as their insights into the peculiar role of the True Sun mentioned in the previous section, promotes the point of view that the Ancient Greek were not ignorant, and saw some of the faults in their models. They just held on to it, since it was most consistent with their philosophy and world view.

Chapter 6

Description of the Antikythera Mechanism

6.1 Initial axioms

At the time, when Derek de Solla Price started his 20-year odyssey of research on the Antikythera Mechanism, only the seven largest fragments of the device were known – Fragments A to G (see Figure 6.1). Somewhere between 1902 and the time when Price began, the smaller parts had been lost in the stores of the National Archaeological Museum of Athens. Price (1974) already speculates about the fact that there must have been more pieces, since old photographs show that fragment C covered more of the lower portion of the main drive wheel on the front of fragment A. In fact, much more such cover can be seen on the photographs, which were taken before cleaning.

A similar fate as the missing pieces, affected the know how about the remaining fragments; it was no longer apparent how the fragments were related. So Price had to start with a puzzle, trying to figure out in which way the fragments were joined in ancient times.

As stated in chapter 2, the first published account of the discovery of the mechanism appeared in the Athens newspaper *To Asty*, on May 23, 1902. The announcement, written by Svoronos, said that the object had been examined, and that it was identified as some sort of an astrolabe, which was contained in a box. It also claimed that the device had been epigraphically dated, through the mirrored lines of inscription that are still visible on Fragment B, to a period extending from about the second century BC. to the first or second century AD. On the same day, Svoronos published a second article in another Athens newspaper, the *Neon Asty* (No. 163), in which he claimed that the object was an astrolabe with spherical projections on a set of rings.

A couple of days later, Konstantin Rados confirmed the inscription in *Neon Asty* (No. 165), but noted the great difficulty in reading them. He also had the opinion that the mechanism looked as if it contained a spring, and suggested, since the excavated statues appeared to be much earlier in date, that the device perhaps came from a second and later ship. A few years later, in 1907, the great classical philologist Albert Rehm entered the arena, postulating his theory about

Figure 6.1: The fragments of the Antikythera Mechanism. The large pieces in the top half are known, from left to right, as Fragments A to G. The pieces in the lower half are known as pieces 1 to 75, these pieces are likely to belong to the Mechanism, however, according to Freeth et al. (2006) this is not definite.

the planetarium of Archimedes. With this, the debate about the origin of the Antikythera Mechanism started. Even though this debate did not present any actual new major investigations of the fragments, they provided a way in for Price, as well as an extensive written account of the ideas that arose before his entry.

Price started to work on the Antikythera Mechanism in 1951, and published his first article on the Mechanism four years later (Price, 1955). Even though there followed several more, in which he describes his new insights (Price, 1956, 1959), obtained through new photographs or fruitful collaboration with other scientists, the real breakthrough presented itself not until 1971.

In that year, Price was alerted by a new publication to the possibility of using gamma-radiography to see through the corrosion and the accretion of the fragments.

6.2 The Fragments

In Figure 6.1, all the surviving fragments of the Antikythera Mechanism are shown, as published in Freeth et al. (2006). The 7 large pieces in the top half of the Figure are known as Fragments A to G – from left to right. The 75 mostly smaller pieces, in the lower half of the Figure, are referred to as pieces 1 to 75.

Figures 6.2 and 6.3 show the front and back faces, respectively, of the largest surviving fragment, being approximately 16 *cm* wide, and 17 *cm* high. One of its main features is the large gear wheel on the front face, but it also directly manifests the complexity of the device; a vast diversity of gears, holes and pegs, on both the front and the back, characterize the ancient complexity of this extraordinary mechanism immediately.

The large gear wheel is now known as the Sun-wheel. It has 224 teeth, and figures as the main drive for the "mechanical computer", in most reconstructions made by now.

The front and back of Fragment B are shown in Figure 6.4. Sub-figure **a** shows the external face, which is covered in a layer of inscriptions in mirror writing, similar to that on Fragment A. These writings were originally a cast of text on the inner face of the back door. Sub-figure **b** shows the internal face, which contains the back of several scale rings, held together with a bridging piece. In sub-figure **b** the remains of a gear and its belonging axis can also be seen (Freeth et al., 2008).

Figure 6.2: Front face of the largest surviving part; Fragment A. One of its main features is the large gear wheel on the front face, but it also directly manifests the complexity of the device; a vast diversity of gears, holes and pegs characterize the ancient complexity of this extraordinary mechanism immediately. The large gear wheel is now known as the Sun-wheel. It has 224 teeth, and figures as the main drive for the mechanical computer, in most reconstructions made by now.

Price (1974) supposed that the inscribed sheet which made the mirror image impressions on both Fragments A and B, was originally much more extensive.

Along lower left-hand corner of the front (Figure 6.2) and the right-hand margin of the back (Fragment 6.3) of Fragment A, there occur small pieces of a brownish rock-like substance adhering to what seems to be the remains of some sort of channel. Though the mechanical details are difficult to see, Price (1974) takes this to be the traces of what once were the wooden side walls of the casting of the instrument. He also refers to Rehm, who mentions a wooden casing, so possibly it was more visible at the time of the discovery, or there existed other fragments of it before his examinations.

The front of Fragment C is shown in Figure 6.5. It displays clear features of a part of dial work at the front, as well as explicit parts of non-mirrored inscriptions,

Figure 6.3: Back face of the largest surviving part; Fragment A. Several different gears can be seen, as well as remains of the case of the mechanism. Main features are the large 223 teeth wheel, and the inscriptions of mirror writing in the right bottom corner.

presumably from the outside of the mechanism.

Fragments D and E are shown in Figure 6.6. Fragment D – left – contains the only gear of thirty surviving gears in the device that is not explained in the model developed by the Antikythera Mechanism Research Project (Freeth et al., 2008, AMRP). Fragment E – right – contains evidence for the Saros eclipse prediction dial as well as inscriptions that refer to the organization of the Metonic calendar.

By the time of Price's analysis and reconstruction, only the largest surviving parts of the Mechanism were known – Fragments A-G in Figure 6.1. During

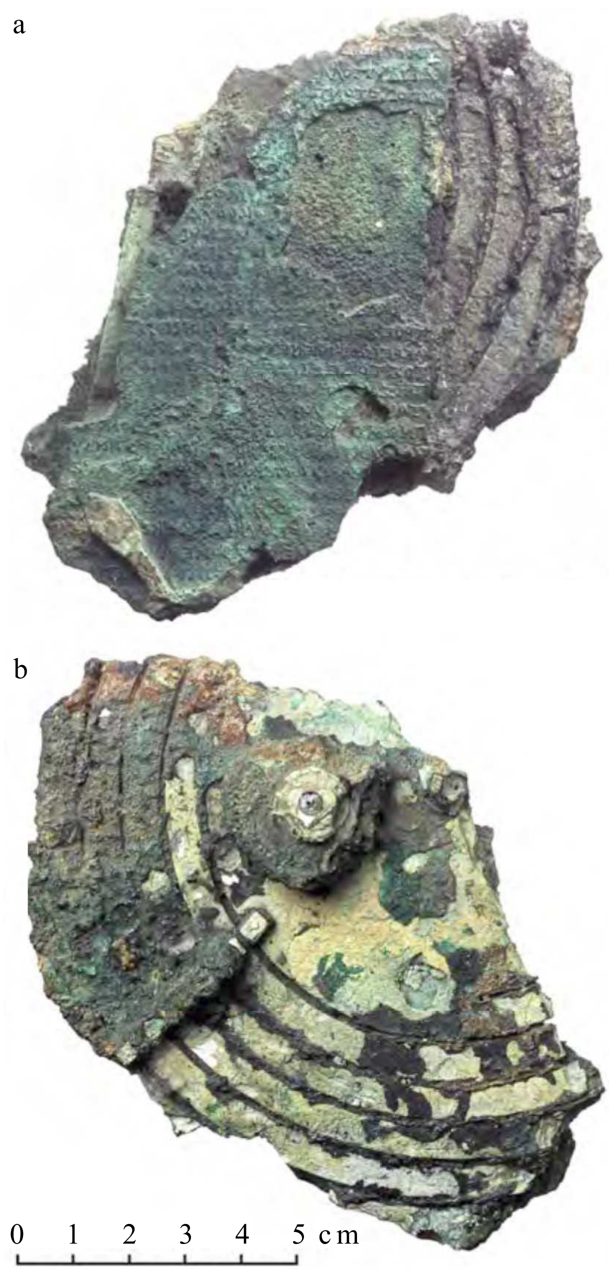


Figure 6.4: Fragment B. Sub-figure **a** shows the external face, which is covered in a layer of inscriptions in mirror writing. These writings were originally a cast of text on the inner face of the black door. Sub-figure **b** shows the internal face, which contains the back of several scale rings, held together with a bridging piece. In sub-figure **b** the remains of a gear and its belonging axis can also be seen.

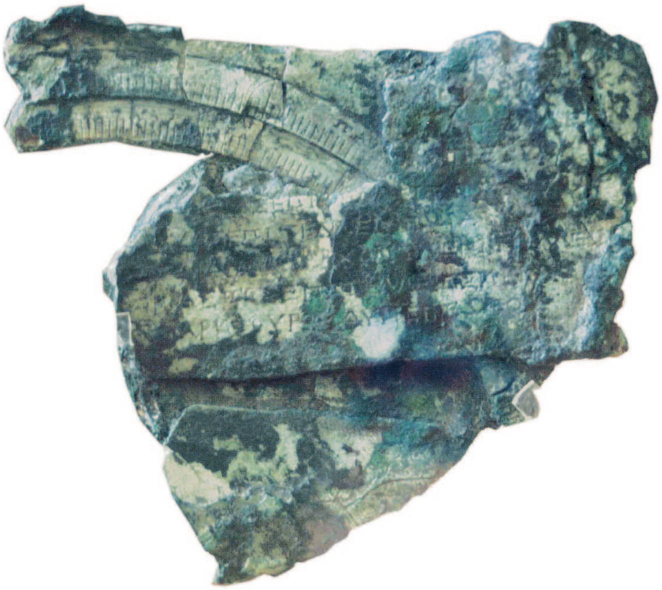


Figure 6.5: Front side of Fragment C. This part features a clear part of the dial work, as well as clear inscriptions from the outside of the case which surrounded the mechanism.

Figure 6.6: Fragments D and E. Fragment D – left – contains the only gear of thirty surviving gears in the device that is not explained in the model developed by the Antikythera Mechanism Research Project (AMRP Freeth et al., 2008). Fragment E – right – contains evidence for the Saros eclipse prediction dial as well as inscriptions that refer to the organization of the Metonic calendar.

extensive searches in the stores of the National Archaeological Museum of Athens, at the beginning of the third millennium, more parts were found. In their paper, Freeth et al. (2006) give an overview of these new finds, which are presented as pieces 1 to 75 in Figure 6.1.

Appendix A.1 consists of an additional series of photographs, showing the three largest Fragments as they are displayed in the National Archaeological Museum. Different side views of the pieces further illustrate the complexity of these surviving elements.

6.3 Price's model

The first gamma and X-ray radio-graphs

When in 1971, through the cooperation with Dr. Ch. Karakalos, and after a painstaking work of preparation, analysis, long exposures and delicate positioning, the first gamma and X-ray radio-graphs were taken, it was immediately evident that much of the gearing was preserved within the fragments. It was Karakalos, who made the first all important counts of gear teeth, a delicate task, tedious and subject to maddening errors and repetitions before consistent results can be obtained. So even though the images were remarkably clear and full of detail, there was much discussion about the actual tooth counts, and the information about the how the gears were meshed was also uncertain. Overall, the evidence was quite incomplete. Nevertheless, much of the form and structure of the gears and the gear trains could be elucidated.

Bit by bit, Karakalos and Price were able to analyze the crucial cases where meshing between certain wheels was doubtful. They examined very carefully the structure of the gears and the gearing of the lower back dial and established their connections with little doubt and to such accuracy, that for the first time the gear ratios could be determined, and associated with well-known astronomical and calendrical parameters.

Joining the main Fragments

Figure 6.7 shows a schematic diagram describing how the four main fragments A-D join together in the Antikythera Mechanism. It shows how the four main parts – fragments A-D – were joined to form a single mass. Figure 6.7 illustrates how fragment C covers the lower left corner of the front of the main fragment A, fragment B covers the top right of the back of Fragment A, and fragment D fits between B and A annular rings of the dial plate of B. According to Price, it was the wooden member, represented by the hatched part indicated with the **x**, whose shrinking may have provoked the splitting apart of the original mechanism.

With the detailed radiography images that provided the evidence for the structure of gears, and with that the gear trains, Price was able to proof that the Antikythera Mechanism is the first known calculator, with the first known scientific scale. Furthermore, he was able to explore the scientific qualities of the gears. The gears are made of bronze sheet about 2 *mm* thick, and metallurgy analysis indicated a low tin composition, with about 95% copper. This indicated that the gears must have been fairly soft and bendy.

Price found the evidence of thirty gears. In order to make his model work, he had to infer two to make his model work. On the gears he did find, he found tooth counts ranging from 15 to 225 teeth.

The first reconstruction

With much of the secrets of the inner Fragments unraveled, and the reconstruction shown in Figure 6.7, Price managed to make a first design of the Antikythera Mechanism. Figure 6.8 shows the front and back face dial plates and the casing of the Antikythera Mechanism. The initial design of the dials is made up out of three concentric displays; one on the front, two on the back. The front dials consist of two large concentric displays, a Zodiac dial with the Greek names of the Zodiac, and a calendar dial, marked with the names of the Egyptian calendar in Greek. Two pointers are present on the display, one represents the position of the Sun, this pointer turns – naturally – once per year. The second pointer gives the average Moon position in the Zodiac, using the Metonic ratio of 254/19 (Zeeman, 1996).

The heart of Price's model is the differential gear. Because such a gear is unknown in Western technology for another 1,600 years, it is an extraordinary conception. The differential has two inputs: the Sun input, which turns at the rate of the Sun through the Zodiac, and the Moon input, which turns at the rate of the Moon through the Zodiac, but in the opposite direction. The output of the differential is the average of this two inputs, and this is used to turn the pointers of the lower dial of the back.

Inside both of the back displays is a small subsidiary dials; one in the upper and one in the lower dial. The pointers on the lower back dials display the age of

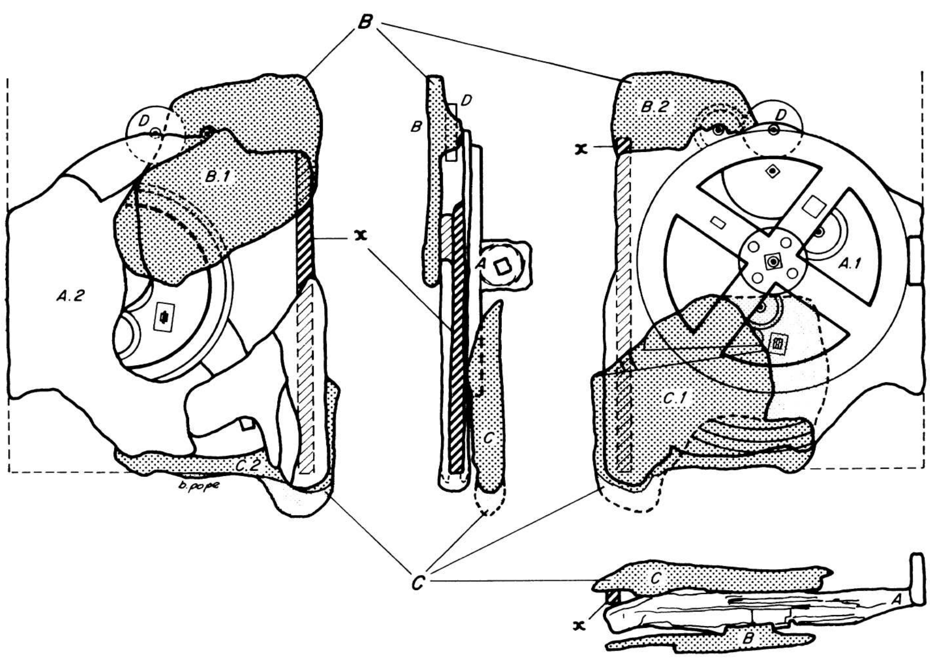


Figure 6.7: Schematic diagram showing how the four main fragments A-D join together in the Mechanism. The back of the mechanism is presented at the left, the front at the right (top). The wooden member whose shrinking may have provoked the splitting apart of the original mass is shown at **x** (Price, 1974).

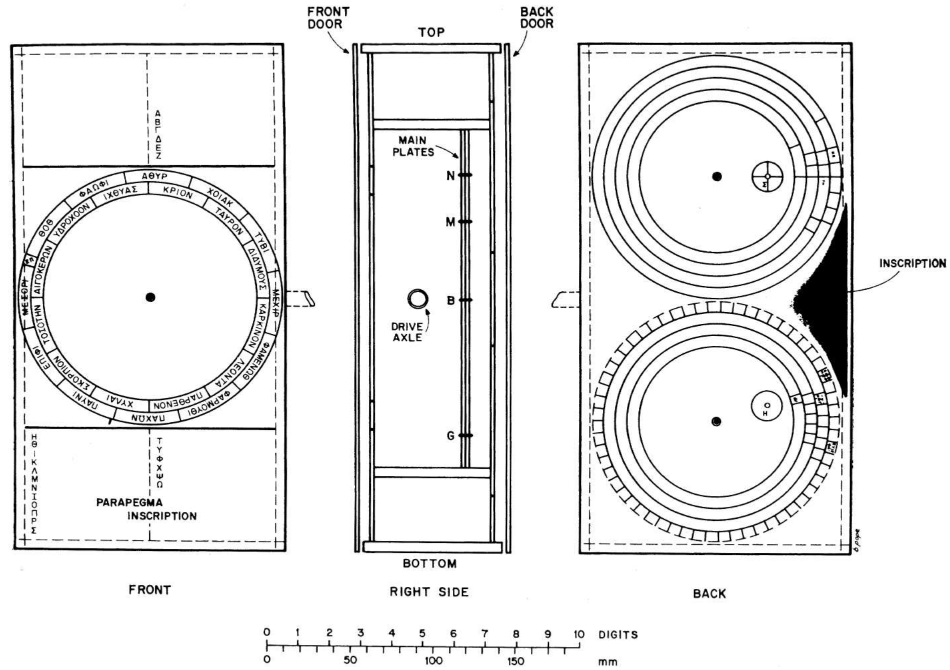


Figure 6.8: First reconstruction of the front and back face dial plates and casing by Price (1974). The initial design of the dial plates is made up out of three concentric displays; one on the front, two on the back. Inside the back displays are two small subsidiary dials; one in the upper and one in the lower dial.

the Moon, referred to as the Synodic Moon, and the Lunar year, on the large and the subsidiary dial, respectively. These pointers are driven by the differential gear. The pointer of the upper large dial represents a four year period. The function of the pointer of the subsidiary dial inside the upper dial is not known in Price's model, as well as the function two gears, used to drive the relevant pointer.

The designed case is astonishingly small, considering the amount of gears and inscriptions the Mechanism contains – only about 13 *cm* high, 17 *cm* wide and 9 *cm* thick.

In Figure 6.9, two different views are shown of a beautiful physical reconstruction of Price's model of the Antikythera Mechanism, made by the Yorkshire-based orrery maker, John Gleave.

Despite its central importance to the history of technology, and as stated in Section 2.4, the volume of literature has been very small and much of the classic research has remained unchallenged for more than a quarter of a century after the works of Price. With the acceptance of the Australian scholar Alan Bromley, who criticized some of Price's findings and challenged whether his model was correct (Bromley, 1990a,b), the subject received hardly any attention.

Over the last decade however, there has been a wave of renewed interest in the Antikythera Mechanism, independently inspired by the British clockmaker Michael Wright and the British astronomer Mike Edmunds. And even though there have been several drastic changes to Price's model, it is important to acknowledge the pioneering nature of his work. As Bromley wrote: *"These criticisms do not belittle work which was a monumental step forward in understanding the Antikythera*

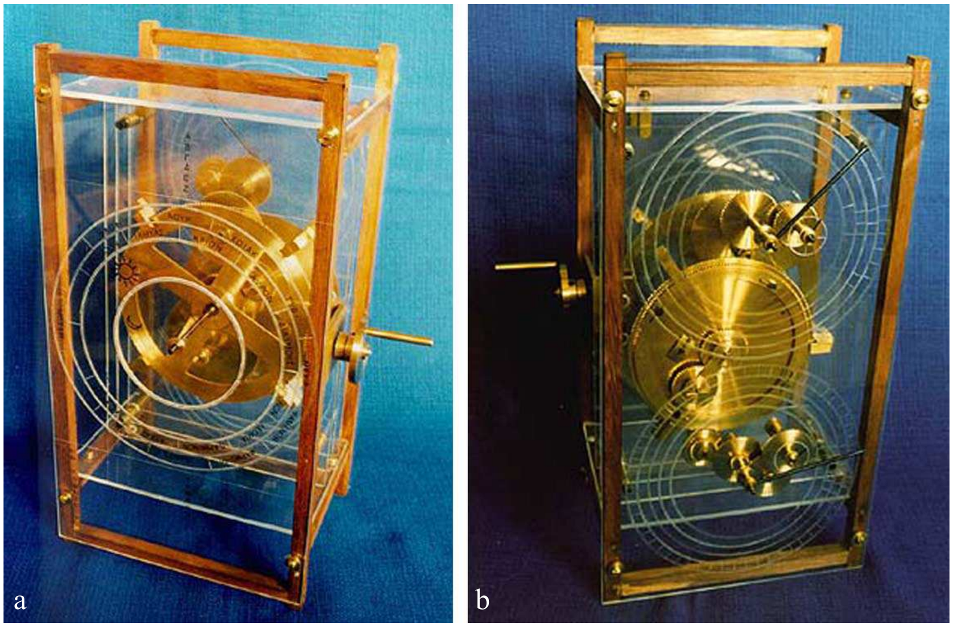


Figure 6.9: Two different views of Price's model of the Antikythera Mechanism, reconstructed by John Gleave. Sub-figure **a** shows the front of the Mechanism, sub-figures **b** shows the back.

Mechanism and a excellent piece of deductive scholarship. It is of the nature of all science that, as Newton suggested, each person can see further into the mysteries of nature only by standing on the shoulders of giants that came before. I could not have done what I have done without standing on Price's achievements" (Bromley, 1990a).

6.4 Contemporary models

(Bromley, 1986, 1990a,b) was one of the first to remark that Price's model did contain several difficulties. Price could find no function for the upper back subsidiary dial, and the pointer for the four year period had no real astronomical significance. Even though four year periods occur in many calendars, there was no clue or reason for the purpose of it in the Mechanism. Furthermore, there were some gears for which Price could find no purpose, this was especially peculiar in the case of a large gear with approximately 222 teeth, right in the centre of the mechanism.

A further difficulty was recognized by Christopher Zeeman, then of Warwick University, who demonstrated that one specific gear train – that of the Metonic cycle, used in the front Moon display – works as a step up ratio of 12 : 1; so one gear has to rotate 12 times, before another gear has rotated once. This would be highly impracticable with the triangular gear teeth that the Mechanism uses. In fact, Bromley showed that the Mechanism needed to be well balanced to work at all, and that it was quite impossible to make practical use of the model as proposed by Price.

Price, it seems, was a little to quick to adopt tooth numbers and arrangements

Figure 6.10: X-ray micro-focus computed tomography (CT) image of Fragment A. Clearly visible are all the inner gears, as well as many of the axes and irregular features. Even more than the outside of the fragment, this image illustrates the enormous complexity of the extraordinary Antikythera Mechanism.

that satisfied his preconceived idea of the nature and function of the Mechanism.

Wright's improvements

Bromley teamed up with the British clockmaker Michael Wright, to make further advances in deciphering the Antikythera Mechanism with the use of digitized X-rays and tomography. By that time, Wright was one of the curators of mechanical engineering at the Science Museum in London. During the eighties, Wright had been involved in the discovery of a simple elementary geared device dated to the sixth century AD., now known as the London Byzantine Sundial-Calendar described by Field and Wright (1985); Wright (1990) . This mechanism led Wright to the existence of the Antikythera Mechanism.

Together, Bromley and Wright achieved better imaging of the Mechanism and obtained some remarkable insights into its functions. Unfortunately, Bromley died in 1999, but this did not stop Wright on his investigations of the Antikythera Mechanism.

Whereas Price worked mainly on an academic level, approaching the Mechanism from the perspective of mathematical and astronomical theory, Wright drew on his vast practical knowledge of arbors, crown wheels, and others mechanical techniques used in gear-train design. This, combined with the better digitized images of the Mechanism resulted in a new model, which is described in a series of papers (Wright, 2003, 2004, 2005a,b,c, 2006).

The Antikythera Mechanism Research Project (AMRP)

Simultaneously with Wright's undertaking, a group of scientists under supervision of the British astronomer Mike Edmunds teamed up in present day Athens to form the Antikythera Mechanism Research Project[1] (AMRP). They also used the newest observational techniques to investigate the Mechanism. First of all, they took three-dimensional X-ray micro-focus computed tomography (CT) images.

Figure 6.10 shows a CT image of Fragments A. Clearly visible are the many smaller gears contained within the artifact. Appendixes A.2 and A.3 contain two series of panels, illustrating this technique. The first shows X-ray images of a rotating Fragment A. The second contains the images of different slices through Fragment A.

This X-ray technique was crucial in making the text just beneath the current surfaces legible. The AMRP also used a polynomial texture mapping (PTM) technique, developed by *Hewlett-Packard Inc.* (Brooks, 2001), to make digital optimized images in order to reveal faint surface details. And in the third place, they used conventional digitized high-quality film photography.

The brand-new model of 2008

In Freeth et al. (2008), most of the work of Wright and the AMRP has resulted into a newly improved model, in which all the gears and dials have a distinct purpose. Figure 6.11 shows the latest schematic gearing diagram, according to Freeth et al. (2008). It underwent some fundamental changes since the 70's. Parts of this model are hypothetical, since the Fragments do not build up into the entire device and several gears are thus missing. However, by deciphering the inscriptions on the Fragments, indications have been found to what both the large and the subsidiary dials display. Figure 6.13 shows a table in which all the gears of the present model are described.

Appendix A.4 shows an alternative view on the schematic gearing of the reconstruction of the Antikythera Mechanism, as proposed by Freeth et al. (2006). Within the series of panels displayed, the build up of the model is shown as well as several views from different angles.

The National Archaeological Museum of Athens became one of the institutions affiliated with the AMRP. This allowed members of the AMRP to search the stores of the Museum and find the 75 smaller pieces, displayed in Figure 6.1. Because

[1] A detailed overview of the work that has been done on the Antikythera Mechanism, both present and in the past, can be seen on the website of the AMRP: *http://www.antikythera-mechanism.gr* .

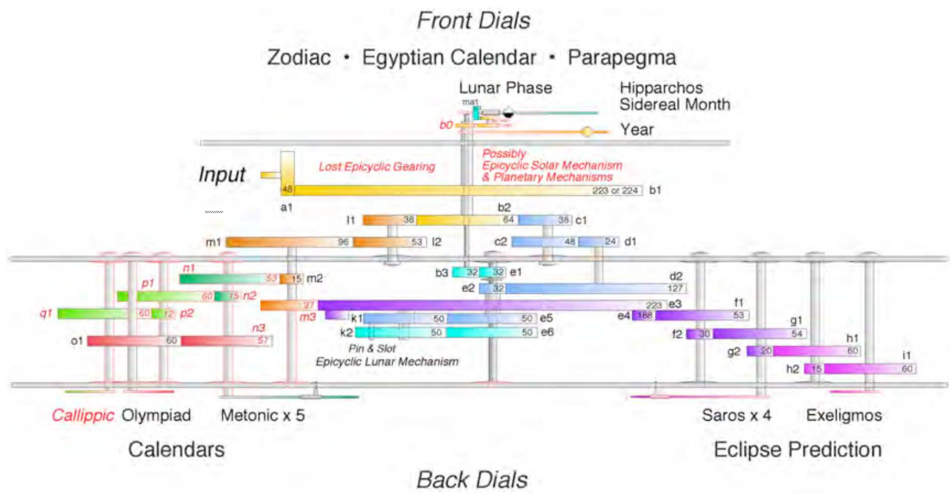


Figure 6.11: Side view of the schematic gearing diagram (not to scale) of the Antikythera Mechanism model by Freeth et al. (2008). Features that are outlines or featured in red are hypothetical. Gears are lettered with their axis, and numbered with increasing distance to the front dial. The two or three digit number on the gear is its actual or assumed tooth count. The pin-and-slot mechanism is located on gears $k1$ and $k2$.

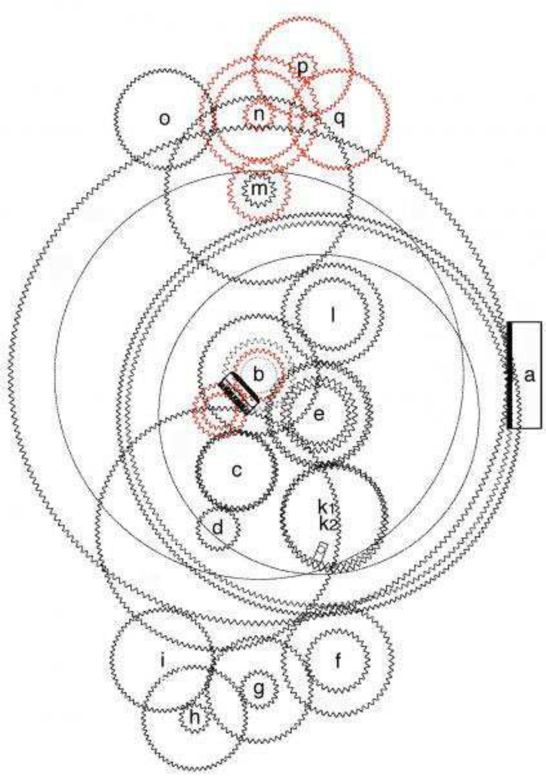


Figure 6.12: Top view of the schematic gearing diagram of the Antikythera Mechanism model by *(Freeth et al., 2008)*. This diagram shows the complexity of the gearing. Gears in black are visible in the X-ray evidence, gears in red are conjectured in order to complete the model.

	Name	Axis	Tooth count	Rotation	Info
1	$a1$	a	–	–	*input*
2	$b0$	b	–	↻	*moon phase*
3	$b1$	b	224	↻	*Sun pointer*
4	$b2$	b	64	↻	
5	$b3$	b	32	↻	*moon pointer*
6	$c1$	c	38	↺	
7	$c2$	c	48	↺	
8	$d1$	d	24	↻	
9	$d2$	d	127	↻	*prime*
10	$e1$	e	32	↺	
11	$e2$	e	32	↺	
12	$e3$	e	223	↺	*prime*
13	$e4$	e	188	↺	
14	$e5$	e	50	↺	
15	$e6$	e	50	↺	
16	$f1$	f	53	↻	*prime*
17	$f2$	f	30	↻	
18	$g1$	g	54	↺	
19	$g2$	g	20	↺	
20	$h1$	h	60	↻	
21	$h2$	h	15	↻	
22	$i1$	i	60	↺	
23	$k1$	k	50	↻	*pin gear*
24	$k2$	k	50	↻	*slot gear*
25	$l1$	l	38	↺	
26	$l2$	l	53	↺	*prime*
27	$m1$	m	96	↻	
28	$m2$	m	15	↻	
29	$o1$	o	60	↻	
30	$m3$	m	27	↻	*hypothetical*
31	$n1$	n	53	↺	*hypothetical, prime*
32	$n2$	n	15	↺	*hypothetical*
33	$n3$	n	57	↺	*hypothetical*
34	$p1$	p	60	↻	*hypothetical*
35	$p2$	p	12	↻	*hypothetical*
36	$q1$	q	60	↺	*hypothetical*

Figure 6.13: Table of observed (1 to 29) and hypothetical (30 to 36) gears in the Antikythera Mechanism, according to Freeth et al. (2008). Given are the name of the gear, the axis of the gear and the tooth count for every gear. The column entitled rotation shows an icon indicating the direction of rotation, as seen when looking through the front of the Mechanism. The last column gives supplementary information.

of this discovery and the new imaging techniques, the AMRP managed to have an enhanced look at the gears inside the Fragments (Freeth et al., 2006), and speculate about corrections to Price's model, much like Wright did. They were able to read and decipher much more of the inscriptions on the Mechanism, which gave away many secrets of the original use and purpose of the device.

The pin-and-slot mechanism

The first concepts of the new gearing were proposed by Wright (2004), made possible because of refined imaging and improved tooth counts. In this model, Price's differential gear had been replaced by a scheme in which we find an even more extraordinary design; a pin-and-slot device. The AMRP publishes the same

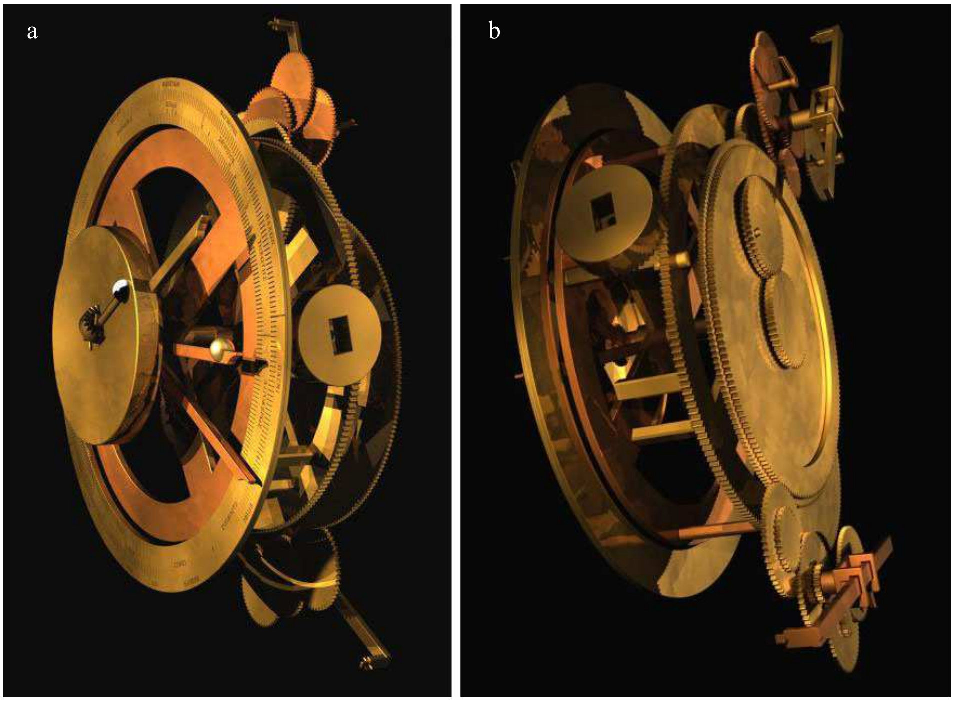


Figure 6.14: Illustration of the gearing in the 2008 Antikythera Mechanism model Freeth et al. (2008). Sub-figure **a** shows the front face of the Mechanism. The elegant design of the half silvered Moon-phase device is seen right at the center, along with the Moon pointer. Sub-figure **b** shows the back of the Mechanism. The four gears of the pin-and-slot mechanism are clearly visible left at the center, as well as the different gear trains leading to the upper and lower back dials.

discovery in Freeth et al. (2006).

The discovery of this technical tour de force was yet another sensational revelation as well as an astounding realization of the theories of Apollonius and Hipparchus (see Section 5.1 and 5.2) in the gearing of the Mechanism. They had developed a theory to explain that it was the eccentric orbit of the Moon that caused the irregularities of the its motion across the sky (Neugebauer, 1983). This non-uniform motion is technically obtained by placing two gears above each other, with axis that are slightly displaced with respect to each other (see Sub-figure **b** in Figure 6.14).

By placing a pin on one gear, and a slot on the other, the gears can pull each other along. The displacement of the axis then translates into the non-uniform motion. Because of this pin-and-slot mechanism, the Moon pointer of the front plate of the Antikythera Mechanism, no longer has a uniform motion when it goes around the dial. In Figure 6.15, an edited slice of a CT scan is shown, on which the remnants of the pin-and-slot mechanism are enhanced. The accompanying panels illustrate the functioning of the pin-and-slot mechanism (Freeth et al., 2006).

Concerning the outer faces

The front dials of the present model now consist of two large concentric displays, a Zodiac dial with the Greek names of the Zodiac, and a calendar dial, marked with

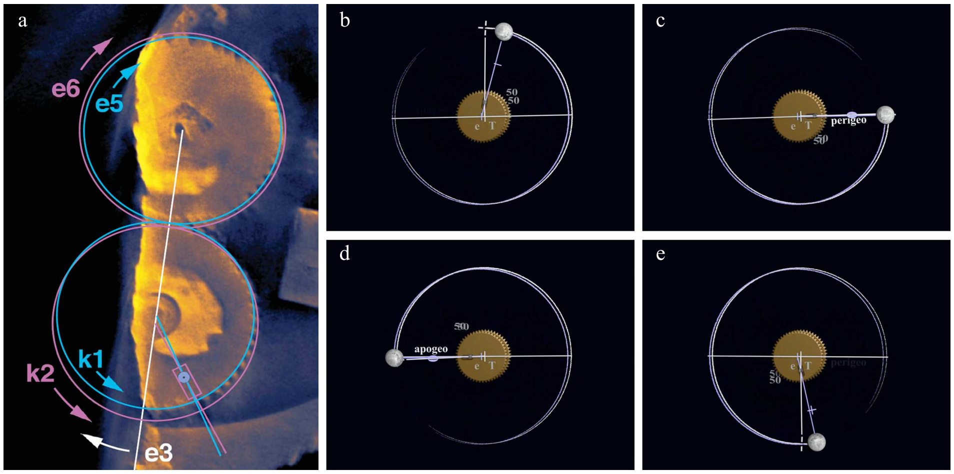


Figure 6.15: The pin-and-slot mechanism. Sub-figure **a** shows an edited slice of a CT scan on which the remnants of the pin-and-slot mechanism are enhanced; gears $e5$ and $e6$ turn on the same axis, while the axis of gears $k1$ and $k2$ are displaced with respect to each other. Through the pin of gear $k1$ and the slot in gear $k2$, they are able to pull each other along with a non-uniform speed. Sub-figures **b** to **e** show four simulations, illustrating the functioning of the pin-and-slot mechanism.

the names of the Egyptian calendar in Greek. This calendar consisted of twelve months of thirty days, and five additional days (called *epagmenai*), which sum up to the 365 days of one year. Because the Egyptian calendar lacked the quarter day of the Solar year, it moved relative to the seasons. This was accommodated on the Mechanism with a movable calendar scale. The scale can be moved by one day every four years, facilitated by a pin on the underside of the scale that engages with a sequence of 365 holes under the calendar scale.

On the calendar scale, a date pointer shows the date in the Egyptian calendar. It is still uncertain whether this pointer also indicated the mean position of Sun (Freeth et al., 2006), or whether there was a separate pointer that displayed the variable speed of the Sun, according to the Solar theory of Apollonius (Wright, 2002a).

Furthermore, the front face contains the pointer that shows the position of the Moon on the Zodiac, that moves with a non-uniform speed, because of the pin-and-slot mechanism.

At the centre of the dial is another ingenious mechanism, which uses a small half-silvered ball to display the phases of the Moon (see Figure 6.14; Wright, 2006).

Through thorough research and recounting, it was Wright who found solid indications that the large dials on the back face were not concentric, but spiral of nature (Wright, 2005a). Within the present model, the large upper back dial is a 19-year (or 235 synodic months) calendar, based on the Metonic cycle (see Section 4.2), arranged as a five-turn spiral (see Figure 6.19). The large lower back dial is a Saros cycle eclipse-prediction dial (see Figure 6.20), arranged as a four-turn spiral of 223 Lunar months, with glyphs indicating eclipse predictions (see Section 4.3).

In both the case of the upper and the lower dial, there is an ingenious reason why the dial is a spiral. The scales of the five-turn Metonic Dial are covered in inscriptions over two or three lines, bounded by scale divisions that define each month of the 235-month scale. Freeth et al. (2008) identify these inscriptions as

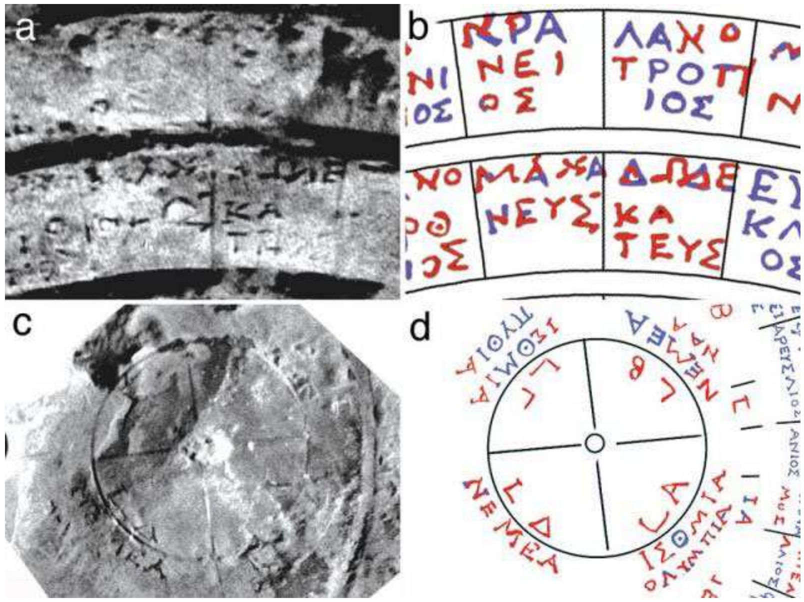


Figure 6.16: Four panels, illustrating observed inscriptions and the reconstructed model. A computer tomography (CT) slice of Fragment B generated from X-ray data (Sub-figure **a**), shows part of the 235-month Metonic dial. The reconstructed text (Sub-figure **b**) is 1.7 millimeters high. Text in red was traced from the CT and revealed the names of the months on the dial for the first time, the text in blue was reconstructed. Sub-figure **c** shows another CT slice through fragment B, on which the Olympiad dial can be seen. Its four sectors display the four-year cycle of the Panhellenic games. A reconstruction of this is shown in the panel of Sub-figure **d**. Again, the text in red is observed, the text in blue is reconstructed (Freeth et al., 2008; Minkel, 2008).

the months and year starts of the Metonic Calendar. Since the Metonic spiral needs 235 cells, to place its 235 months, the dial is curled up into one spiral, which indicates that the pointer will go around five times in one Metonic cycle.

In terms of months, the Saros cycle is equal to 223 synodic months, 242 draconic months and 239 anomalistic months. The *Full Moon Cycle* is the cycle of changes in diameter of the full Moon, which depends on how close the Moon is to the Earth in its elliptic orbit (see Appendices 4.1 and 4.3). This is the same period the Sun takes – as seen from the Earth – to complete an orbit relative to the Moon's perigee. It can be seen as the beat period of the synodic and the anomalistic months. Now, the Saros cycle implies that there are $239 - 223 = 16$ *Full Moon Cycles* per Saros cycle. This means, with respect to the four-turn spiral, that each quarter turn of the Saros Dial is a *Full Moon Cycle*, and the angle of the Saros pointer within the Dial indicates the phase of the cycle. Since the diameter of the Moon mediates both the length and the type of eclipse – for example, when the Moon's apparent diameter is small, a Solar eclipse may be annular rather than total – this four-turn spiral provides additional information about the type of eclipses.

Inside both the upper and lower spiral dials, one finds subsidiary dials. Within the Metonic dial in Figure 6.19 are two subsidiary dials shown, as identified by Freeth et al. (2008). The right one represents the Olympiad dial; a staggering discovery which indicates that the Mechanism was additionally used to link the technical calendars, used by astronomers, to everyday calendars that regulated ancient Greek society.

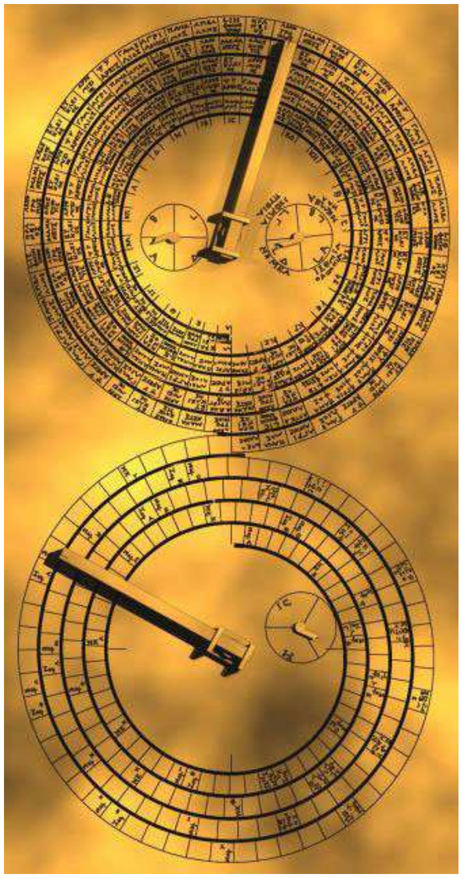


Figure 6.17: A computer-generated reconstruction illustrating the back dials of the Antikythera mechanism. The upper spiral dial is a 19-year, 235-month Metonic calendar for fitting lunar months into solar years. The right subsidiary dial follows the four-year cycle of Panhellenic games, including the Olympic games and the Nemean games. The left subsidiary dial is the hypothetical Callippic dial. The lower spiral dial is an 18-year Saros calendar for predicting solar and lunar eclipses. Inside this Saros dial, is a smaller dial representing the Exeligmos (Minkel, 2008).

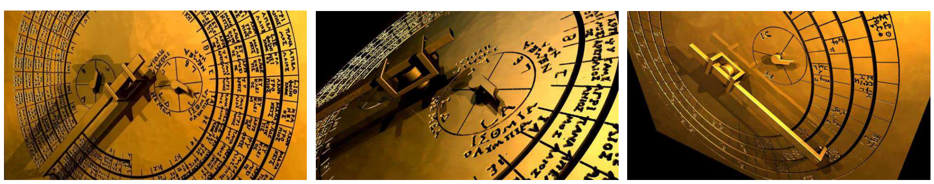


Figure 6.18: Three plates of the reconstruction of the Antikythera Mechanism, illustrating the details of the back face. The left panel illustrates details of the Metonic cycle and the Olympiad dial (inner right). The markings on the calendar, which are inscribed between divisions on the dial, indicate the names of the months and the start of each year. The middle panel contains the Olympiad dial showing the four-year cycle of Panhellenic games. The right panel illustrates a close-up view of the mechanism's lower back dial, which predicted eclipses based on the 18-year, 223-month Saros calendar. Glyphs inscribed on the dial indicate eclipse times, and the smaller, inner dial shows the Exeligmos. This adds a necessary correction to the predicted eclipse times for successive turns around the main dial (Freeth et al., 2008; Minkel, 2008)

The Olympic Games marked the beginning of a four year time-span called an Olympiad. This was a calendar system shared by all the Greek cities, bringing some uniformity to the chronology of the Hellenistic world. The Games began on the full Moon closest to the summer solstice which indicated that calculating the timing required expertise in astronomy. In ancient Greece, the Olympic Games were the most prestigious of four sets of games, called the Panhellenic Games.

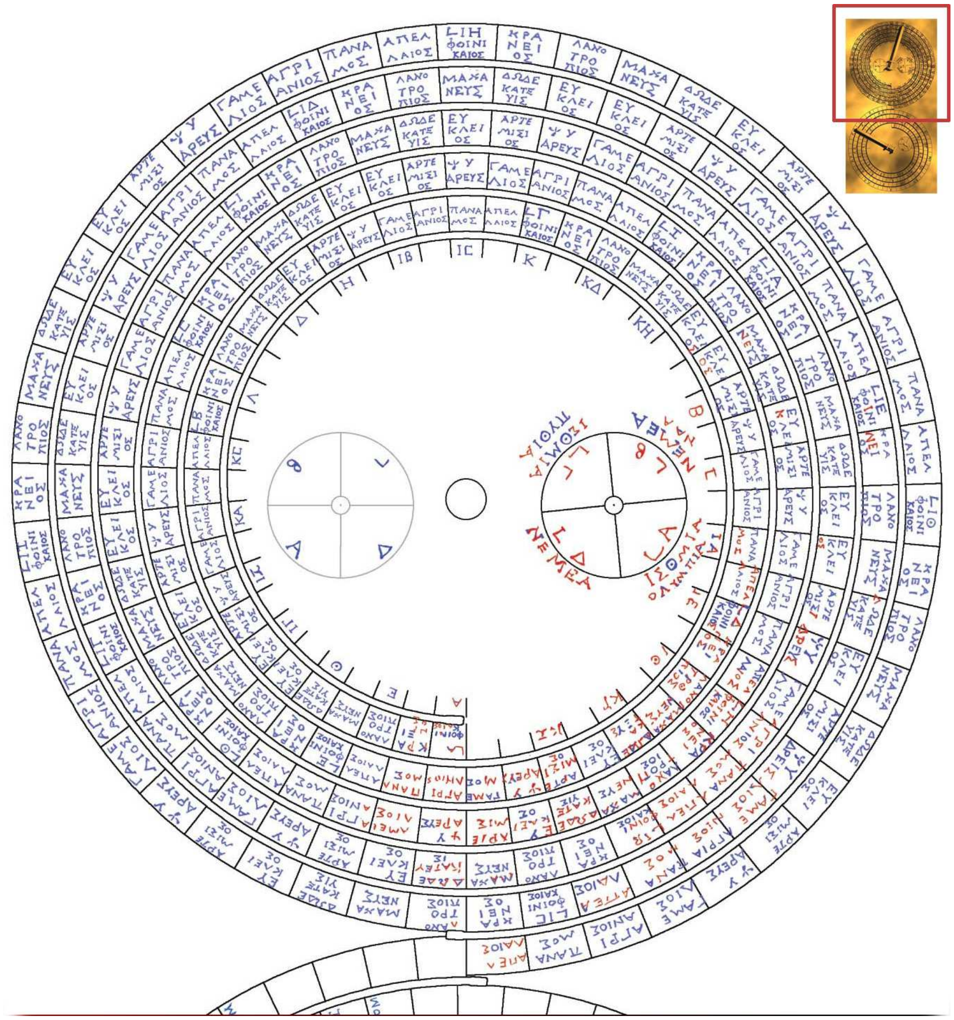


Figure 6.19: Representation of the upper back dials of the Antikythera Mechanism. The large spiral shaped dial represents the 19-year, 235 month Metonic cycle (see Section 4.2). The inscriptions display the name of the month in the 235 months within the Metonic cycle. The red text is traced from evidence, the blue text is reconstructed (Freeth et al., 2008). Within the spiral dial are the two subsidiary dial; one for the Panhellenic Games (right) and one for the Callippic cycle (left).

In the first year of the subsidiary dial are the Isthmian games in Corinth and the Olympic games in Olympia. Year two contains the Nemean games in Nemea and the Naian games in Dodona. The third year hosts the Isthmian games in Corinth and the Pithian games in Delphi, and in year four are the Nemean games again and a yet undeciphered game (Freeth et al., 2008). First recorded in 776 BC., the ancient Olympic Games were extinguished by the Christian Roman emperor Theodosius I in around 394 AD.

The left subsidiary dial in Figure 6.19, is the hypothetical Callippic dial. In several models after Price's, but prior to the present one, the Olympiad dial was thought to be a Callippic Dial (Wright, 2005a), representing the 76-year Callippic

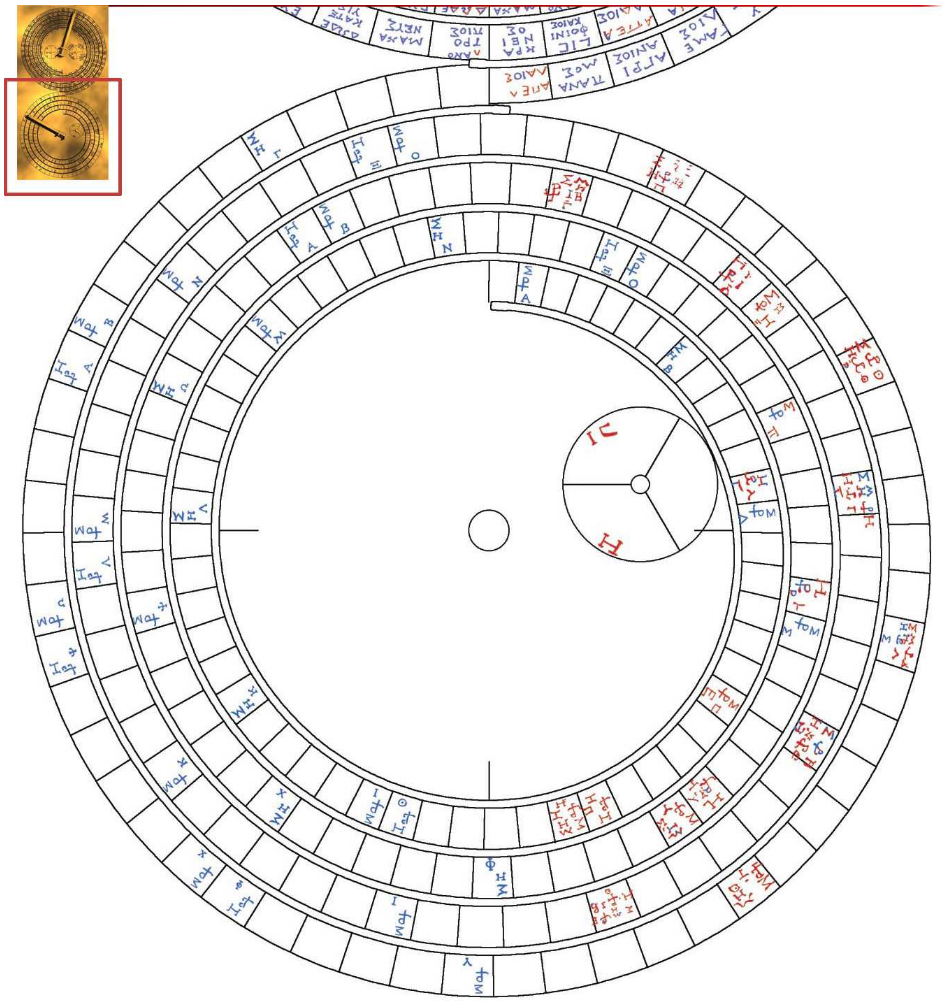


Figure 6.20: Representation of the lower back dials. The large dial represents the 18-year Saros cycle (see Section 4.3). The glyphs indicate eclipse predictions. The red glyphs are traced from evidence and the blue glyphs are reconstructed (Freeth et al., 2008). Within the Saros dial is a smaller subsidiary dial, representing the Exeligmos.

Cycle (see Section 4.2). This was considered plausible for a number of reasons, indicated by the inscriptions found on the Fragments and by the arrangement and purpose of the other pointers. Freeth et al. (2008) therefore favour a second subsidiary dial inside the Metonic Dial, placed symmetrically to the Olympiad Dial so it can be driven by the mirror image of the gearing originally purposed for this dial.

The subsidiary dial inside the lower spiral dial, shown in Figure 6.20, represents the Exeligmos Dial. This is an improvement on the Saros cycle, and can be used to predict at what time of the day an eclipse is going to occur (see Section 4.3 Freeth et al., 2008).

Chapter 7

Redesigning the planetary extension

Concerning the research described in the previous chapters, there are solid arguments to assume that the Antikythera Mechanism also contained the representation for the motions of the planets. The five arguments put forward in Chapter 1 of this thesis, are of crucial importance in this respect.

For this model, we employ the planetary theories developed by Apollonius of Perge. This model is not exact, but it predates the Antikythera Model, and lends itself to a mechanical representation. Furthermore, this epicycle model was further adjusted by Hipparchus, who was also responsible for the epicyclic modelling of the Lunar orbit entailed in the pin-and-slot mechanism. And even though, the indications are circumstantial, the identification of Rhodes as a likely source for the mechanism (Price, 1974), puts it, figuratively speaking, almost into Hipparchus' lap: Hipparchus lived – and died in approximately 120 BC. – on the island Rhodes.

Since we have to relate multiple quantities to the Sun and each of the different planets in a comprehensive manner, we will do so by placing a corresponding symbol to the quantity as sub-script. For each of the celestial objects, the following symbol is used:

$$\begin{aligned} Sun &= \odot \\ Mercury &= ☿ \\ Venus &= ♀ \\ Mars &= ♂ \\ Jupiter &= ♃ \\ Saturn &= ♄ \end{aligned}$$

7.1 The Lunar gears in the Antikythera Mechanism

To be able to appreciate the working of the device, we take a look at the presented Lunar model in the Antikythera Mechanism. Zeeman (1996) describes the model for the mean motion of the Moon clearly: in one revolution of the Sun around the Earth, the Moon has to make 13.3687 revolutions, or 13.3687 sidereal Lunar cycles. Thus, the gear ratio should be 1:13.3687; which is defined the ratio of revolutions for the Moon.

Following the gear train in the Antikythera Mechanism – which needs a slight adjustment for the model of Freeth et al. (2008) – we get the following relation:

$$\begin{aligned} \textit{mean Moon gear ratio} &= \frac{b2}{c1} \times \frac{c2}{d1} \times \frac{d2}{e2} \times \frac{e1}{b3} \\ &= \frac{64}{38} \times \frac{46}{24} \times \frac{127}{32} \times \frac{32}{32} \\ &= \frac{254}{19} \\ &= 13.3684\,, \end{aligned}$$

where the gears are given, according to the definition presented in the table of Figure 6.13. The gears denoted in the fractions, are the gears that tumble into each other (see Figure 7.1), the cross sign $\times$, indicates that the motion is carried over through an axis (see Figure 7.2).

In order to quantify the accuracy of this outcome, we introduce the following expression:

$$\frac{1}{\alpha} = \frac{\check{\nu} - \nu}{\nu}\,. \tag{7.1}$$

Here, α is the accuracy, ν is the observed ratio of revolutions, and $\check{\nu}$ is the ratio of revolutions, as obtained by the gears in the gear train (Raimond, 1934).

When we use Equation 7.1 with the ratios of revolution acquired for the Moon, we get the following accuracy:

$$\frac{13.3684 - 13.3687}{13.3687} = -2.2 \times 10^5 = \frac{-1}{4.6 \times 10^4}\,.$$

In words: when the pointer of the Sun has traveled around the display, for more than 44 thousand degrees – or more than $44,562/360 \sim 124$ years – the Moon will not be off for more than 1 degree on the dial.

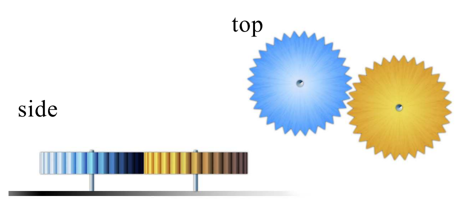


Figure 7.1: Top and side view illustrations of inter-meshing gears. Shown are two gears that tumble into each other. If the yellow gear has n_1 teeth, and the second blue gear has n_2 teeth, then the gear ratio is given by n_1/n_2. When the yellow gear makes one revolution, the blue one makes n_1/n_2 revolutions.

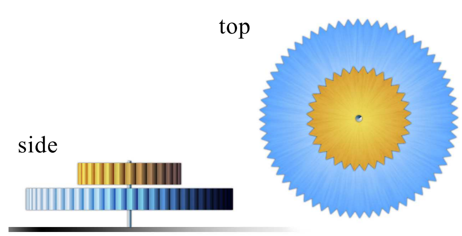


Figure 7.2: Shown are a top view and a side view of two gears that rotate on the same axis. In this way, the motion of on gear can be carried over to another gear, with the condition that both gears make one revolution in the same time, with the same speed. This manner of transferring motion is indicated by the symbol $\times$.

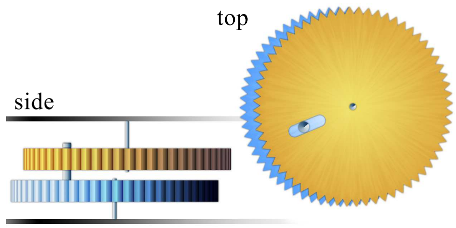


Figure 7.3: Top and side view illustrations of pin-and-slot gearing. In this arrangement, the motion is not carried over with uniform velocity. The pin on the blue gear, pulls the yellow gear along. Because the axes are displaced, this results in a non-uniform motion. The overall orbital period does not change. This manner of transferring motion is found in the Antikythera Mechanism (see Section 6.4), and is indicated by the symbol $\tilde{\times}$.

The models by Freeth et al. (2006, 2008) contain the pin-and-slot mechanism (see Figure 7.3) for the Moon, placed inside the gear train of the Lunar motion. This does not, however, affect the period of one sidereal month. When we do incorporate this mechanism into the gear train, and follow the actual model, we get the following train:

$$\textit{Moon gear ratio} = \frac{64}{38} \times \frac{46}{24} \times \frac{127}{32} \times \frac{50}{50} \tilde{\times} \frac{50}{50} \times \frac{32}{32} ,$$

where the $\tilde{\times}$ indicates that the motion is not carried over through an normal axis, but by means of a off-centre pin-and-slot mechanism. Still, as can easily be seen, the additional multiplications of two times 50/50 cancel out in the sidereal orbital time. One must only be careful, in the case of the calculated error the amount of 1 degree is not longer constant, so this becomes a mean error, and the accuracy becomes a mean accuracy.

7.2 Determining necessary orbital periods

In order to look for appropriate gears and corresponding gear trains, used to propel the dials of each planet, we audition a similar path as with the Lunar dial. First, we determine the gear trains for the mean motions of the planets – which in the deferent-and-epicycle model is the motion of the centre of the epicycle along the deferent – thereafter, we incorporate the motions of the epicycles, in order to fit the corresponding dial motion to the planetary theory of Hipparchus.

Inferior planets

As we have seen in Equation 5.1 of Section 5.1, the direction from the Earth to the mean Sun always coincides with the direction from the Earth to the epicycle's centre on the deferent. Figure 5.5 illustrates this relation. The orbital time of one revolution for both Mercury and Venus is thus 1 tropical year.

The orbital time for one revolution of the planet on its epicycle is equal to its synodic period. As described in Section 4.1, a synodic month is the period in which the Moon makes one trip around the Earth, and returns to the same place in the sky, with respect to the Sun. So, this is the period from one Full Moon to the next. For a planet, this definition is also applicable, with the only exception that a planet, off coarse, makes a trip around the Sun instead of around the Earth.

The synodic period of a planet is fairly straightforward to calculate. Let p be the sidereal period for the planet around the Sun in Julian years. Then, the synodic period is given by (Freeth, 2002a):

$$t = \frac{p}{p-1} \tag{7.2}$$

For Venus, $p_{♀} = 0.615187\ yr$ (de Pater and Lissauer, 2004). Equation 7.2 then indicates that it synodic period is $s_{♀} = 1.59864\ yr$. A similar exercise shows that Mercury, which has a sidereal period of $p_{☿} = 0.240844\ yr$, has a synodic period of $p_{☿} = 0.317253$ yr.

Now that we know the synodic periods of the inferior planets, we can also calculate the number of synodic revolutions they make in one year, through the simple relation:

$$\mu = t^{-1} = 1 - \frac{1}{p}\ , \tag{7.3}$$

where the latter is the solution obtained through the substitution of Equation 7.2.

From Equation 7.3 we find for Mercury that $\mu_{☿} = 3.15206\ yr^{-1}$, and for Venus that $\mu_{♀} = 0.625533\ yr^{-1}$.

Superior planets

A superior planet moves around its deferent in a pace equal to its sidereal period. Thus, Mars goes round in $p_{♂} = 1.88071\ yr$, Jupiter in $p_{♃} = 11.8565\ yr$ and Saturn in $p_{♄} = 29.4235\ yr$ (de Pater and Lissauer, 2004).

In one year, Mars proceeds through $1/p = 0.531714$ part of its sidereal orbit. The sidereal ratio of revolutions for Mars is therefore given by: $\nu_{♂} = 0.531714\,yr^{-1}$, which describes the general expression:

$$\nu = p^{-1}. \tag{7.4}$$

The sidereal ratios of revolution for the other four planets can be found in a similar way: Mercury $\nu_{☿} = 4.15206\ yr^{-1}$, Venus $\nu_{♀} = 1.62553\ yr^{-1}$, Jupiter $\nu_{♃} = 0.0843418\ yr^{-1}$, and Saturn $\nu_{♄} = 0.0339864\ yr^{-1}$ (de Pater and Lissauer, 2004).

The orbital time for one revolution on the epicycle, is presented in the same manner as with the inferior planets; it also takes one synodic period to complete the circle. With Equation 7.2, and the sidereal periods of above, the synodic periods can be calculated: the synodic period of Mars is $p_{♂} = 2.13544\ yr$, that of Jupiter is $p_{♃} = 1.09211\ yr$ and that of Saturn is $p_{♄} = 1.03518\ yr$.

With the use of Equation 7.3, we can now also obtain the synodic ratios of revolution for the superior planets: we find for Mars that $\mu_{♂} = 0.468286\ yr^{-1}$, for Jupiter that $\mu_{♃} = 0.915658\ yr^{-1}$ and for Saturn that $\mu_{♄} = 0.966013\ yr^{-1}$.

7.3 Composing planetary gear trains

Factorizing orbital periods

The next step, is to find a ratio of two integers, that is equal to the found ratios of revolution. In the case of the Moon, this was the ratio of 254 over 19. For the planets, we make use of the fact that – if we define the two integers we are looking for as I_1 and I_2 – the relationship should be:

$$ratio\ = \frac{I_1}{I_2}\ . \tag{7.5}$$

This Equation is suitable for both the synodic period μ and the sidereal period ν.

In the case of the latter, it can easily be rewritten as $I_2 \cdot \nu = I_1$. If we then use a simple computer program, in which an array P is defined containing all integers between 1 and 10,000, there is an easy way to find values for I_1 and I_2. Note that the integers I_1 and I_2 can be seen as the number of sidereal periods that have passed, when the planet and the Earth, which are thus represented by I_1 and I_2 respectively, have reached the same relative position in the sky.

We check for every value of P, whether its product with ν obeys the boundary condition that its outcome is an integer. Since the product will almost never be exactly zero, we introduce a margin of 1/100, wherein the product must be an integer; so, for instance, if $P_i \cdot \nu = 367.992$, it will be seen as a possible solution, if $P_i \cdot \nu = 367.989$, it will not be seen as a possible solution.

After this step, we take all solutions and evaluate their accuracy ν, as defined in Equation 7.1. This provides us with a manner of sorting the solutions according to their accuracy, and thus eventually with the most accurate estimate of integers I_1 and I_2. For instance, in the case of Mars these values are $I_1 = 5231$ and $I_2 = 9838$, in the case of Mercury these values are $I_1 = 34624$ and $I_2 = 8339$.

However, these are not the optimal results for our search of I_1 and I_2. Looking at the results for Mars, one may notice that the integer 5231 is a prime number. It is straightforward to see that a gear wheel of 5231 teeth is somewhat of a problem, to say the least. There are ways of dealing with gear ratios and large primes, because they can be approximated by other ratios. Hayes (2000) describes how to accomplish this. However, a simpler way is to factorize the inferred integers into their smallest parts. For Mars we find that $I_1 = 5231$, and $I_2 = 2 \cdot 4919$. For Mercury that $I_1 = 2^6 \cdot 541$, and $I_2 = 31 \cdot 269$; also these leave much to be desired.

Thus, our next step is to factorize every found solution, and check what size the largest factor is (Raimond, 1934). As a boundary condition, we pose that there the largest factor may not be larger that the largest tooth count found in the Antikythera Mechanism, which is 224.

Inferior planets

Figure 7.4 shows two plots concerning the synodic periods of the inferior planets, where the accuracy α is plotted against the largest factor, for each possible solution of Equation 7.5, when $I_2 < 10.000$. The green area indicates an accuracy $\alpha > 10^6$, the blue area indicates the values of the found gears in the Antikythera Mechanism, thus $20 <$ factor < 224. The plots demonstrate that there are multiple possibilities in gearing the desirable gear ratios. The factorized synodic orbital ratios, corresponding to the points with an accuracy $\alpha > 10^6$ and a largest factor smaller than 224, are listed in the table of Figure 7.5. Figure 7.8 shows a histogram displaying the number of possibilities.

We immediately see that the synodic orbit for Mercury is only described by one set of factors, namely $\nu_{☿} = 3 \cdot 13 \cdot 59 \;/\; 2 \cdot\; 5 \cdot 73$. For Venus, there are already ten different possible set of factors.

Superior planets

Figure 7.6 shows a series of plots concerning the sidereal and synodic periods of the superior planets. The same methods and boundary conditions as in Figure 7.4 are applied. And as with the found possible factors for the inferior planets,

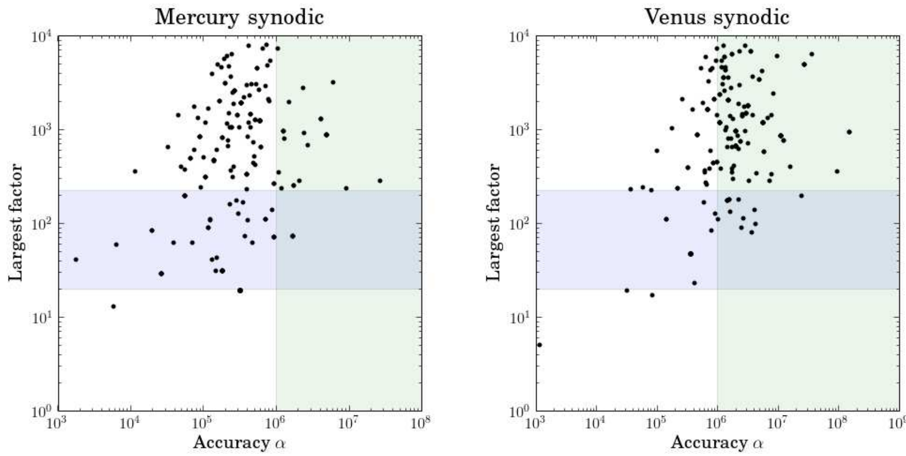


Figure 7.4: The accuracy α plotted against the largest factor, for each possible solution of Equation 7.5, when $I_2 < 10.000$. The green area indicates an accuracy $\alpha > 10^6$, the blue area indicates the values of the found gears in the Antikythera Mechanism, thus $20 <$ factor < 224.

			Factors	Accuracy α ($\times 10^6$)
Mercury	Synodic period:	1	$3 \cdot 13 \cdot 59 \ / \ 2 \cdot \ 5 \cdot 73$	1.73
Venus	Synodic period:	1	$41 \cdot 193 \ / \ 2 \cdot 5^2 \cdot 11 \cdot 23$	24.8
		2	$2 \cdot 37 \cdot 97 \ / \ 3^3 \cdot 5^2 \cdot 17$	4.26
		3	$2 \cdot 3^3 \cdot 5 \cdot 19 \ / \ 59 \cdot 139$	4.16
		4	$2^3 \cdot 23 \cdot 47 \ / \ 5^2 \cdot 7 \cdot 79$	3.72
		5	$2^4 \cdot 3 \cdot 113 \ / \ 13 \cdot 23 \cdot 29$	2.66
		6	$3^2 \cdot 5 \cdot 179 \ / \ 79 \cdot 163$	2.27
		7	$2^2 \cdot 7 \cdot 11 \cdot 29 \ / \ 109 \cdot 139$	1.65
		8	$3^4 \cdot 47 \ / \ 2 \cdot 17 \cdot 179$	1.60
		9	$19 \cdot 131 \ / \ 23 \cdot 173$	1.45
		10	$47 \cdot 102 \ / \ 71 \cdot 109$	1.03

Figure 7.5: Factorized synodic orbital ratios for the inferior planets, arranged according to their accuracy.

the factors able to describe the sidereal and synodic orbital periods, that obey the boundary conditions of $\alpha > 10^6$ and a factor not larger than 224, are listed in the table shown in Figure 7.7. Figure 7.8 shows a histogram displaying the different number of possibilities for these orbital periods.

The different plots, as well as the table show that there are various possibilities to factorize the different ratios. Only in the two cases for the sidereal periods of Jupiter and Saturn, the possibilities are few.

7.4 Disadvantages of the pin-and-slot mechanism

The next step in creating the planetary extension for the Antikythera Mechanism, is relating the factors found in the previous section, to actual tooth counts, and with that, to gears and gear trains. But before we do that for all the planets, it is instructive to have a closer look at the pin-and-slot device present in the

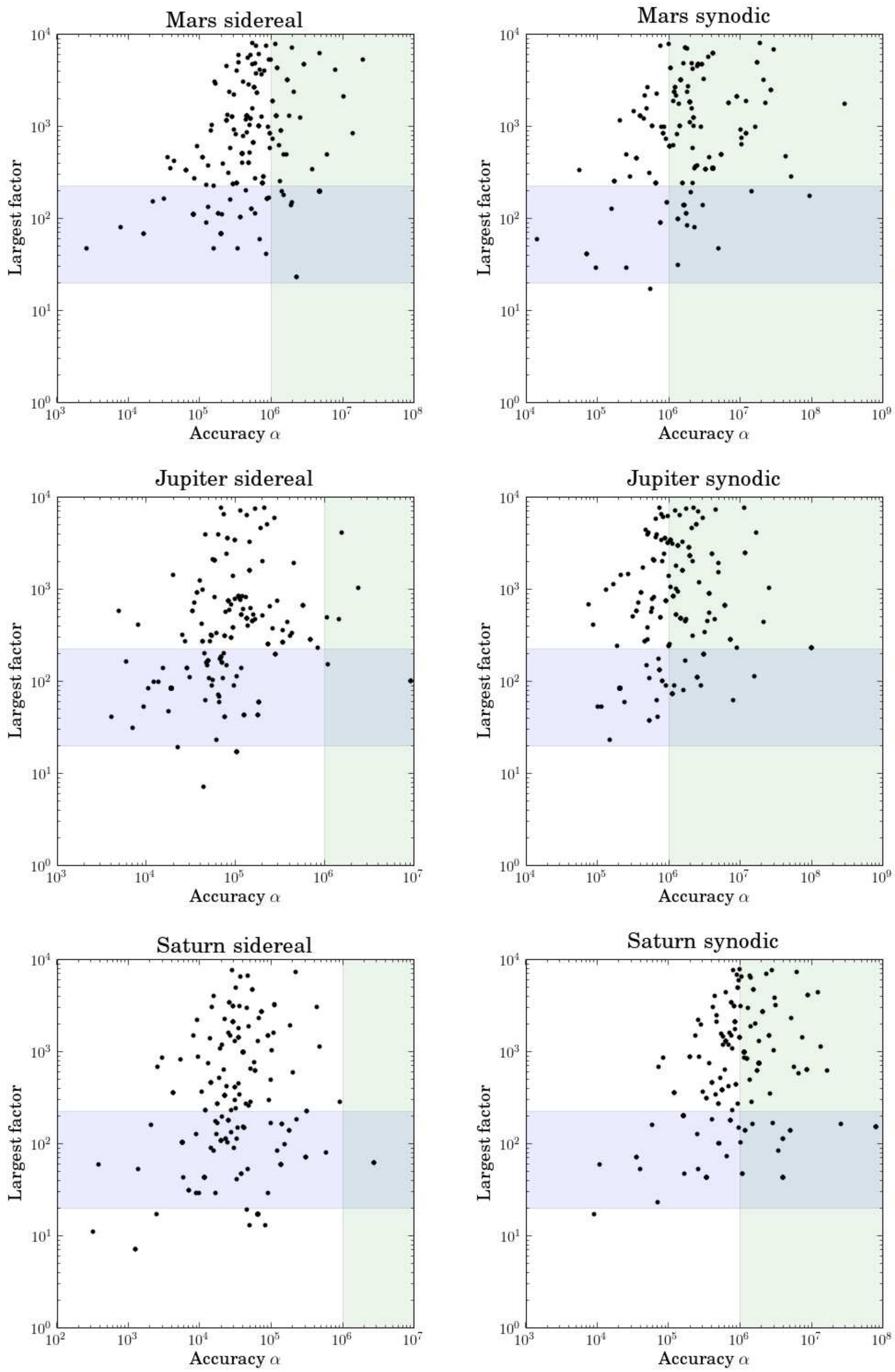


Figure 7.6: The accuracy α plotted against the largest factor, for each possible solution of Equation 7.5, when $I_2 < 10.000$. The green area indicates an accuracy $\alpha > 10^6$, the blue area indicates the values of the found gears in the Antikythera Mechanism, thus $20 < \text{factor} < 224$.

Antikythera Mechanism. The elegant solution, as used in the Antikythera Mechanism, also has its disadvantages.

In order to explain these disadvantages, we have to return to the Lunar model. In the model of the Moon of Hipparchus and Apollonius, as described in Sections 5.1, the Moon rotates round its deferent in the time of one sidereal period. Freeth et al. (2006) state that the period it takes the Moon to make one revolution on its

			Factors	Accuracy α ($\times 10^6$)
Mars	Sidereal period:	1	$2 \cdot 197 \ / \ 3 \cdot 13 \cdot 19$	4.82
		2	$3^3 \cdot 7 \cdot 11 \ / \ 2 \cdot 5 \cdot 17 \cdot 23$	2.26
		3	$31 \cdot 149 \ / \ 7 \cdot 17 \cdot 73$	2.00
		4	$5^2 \cdot 13^2 \ / \ 2 \cdot 29 \cdot 137$	1.90
		5	$17 \cdot 179 \ / \ 59 \cdot 97$	1.54
		6	$2^5 \cdot 3 \cdot 31 \ / \ 29 \cdot 193$	1.43
	Synodic period:	1	$5 \cdot 11 \cdot 109 \ / \ 2 \cdot 37 \cdot 173$	96.1
		2	$41 \cdot 197 \ / \ 3^5 \cdot 7^2 \cdot 11$	14.6
		3	$2 \cdot 5 \cdot 7^2 \cdot 19 \ / \ 3^2 \cdot 47^2$	5.02
		4	$2^2 \cdot 13 \cdot 139 \ / \ 3^2 \cdot 5 \cdot 7^3$	3.08
		5	$2^2 \cdot 29 \cdot 59 \ / \ 5 \cdot 37 \cdot 79$	2.31
		6	$2^4 \cdot 11 \cdot 31 \ / \ 61 \cdot 191$	2.07
		7	$2 \cdot 31 \cdot 83 \ / \ 3^3 \cdot 11 \cdot 37$	1.81
		8	$2^2 \cdot 3^2 \cdot 113 \ / \ 7117173$	1.76
		9	$62^2 \ / \ 2 \cdot 29 \cdot 137$	1.67
		10	$3 \cdot 5 \cdot 11 \cdot 43 \ / \ 109 \cdot 139$	1.62
		11	$3^5 \cdot 23 \ / \ 5 \cdot 7 \cdot 11 \cdot 31$	1.37
		12	$2^3 \cdot 5 \cdot 67 \ / \ 59 \cdot 97$	1.35
Jupiter	Sidereal period:	1	$2 \cdot 5 \cdot 23 \ / \ 3^3 \cdot 101$	9.40
		2	$3 \cdot 151 \ / \ 131 \cdot 41$	1.09
	Synodic period:	1	$2 \cdot 3 \cdot 5 \cdot 13^2 \ / \ 7^2 \cdot 113$	16.0
		2	$2^5 \cdot 5 \cdot 61 \ / \ 3 \cdot 11 \cdot 17 \cdot 19$	8.16
		3	$2^2 \cdot 5 \cdot 7 \cdot 67 \ / \ 2^2 \cdot 13 \cdot 197$	3.10
		4	$7 \cdot 13 \cdot 89 \ / \ 5 \cdot 29 \cdot 61$	2.84
		5	$2 \cdot 5^2 \cdot 109 \ / \ 2^6 \cdot 3 \cdot 31$	2.54
		6	$2 \cdot 17 \cdot 167 \ / \ 3 \cdot 13 \cdot 53$	1.75
		7	$5 \cdot 11^3 \ / \ 2^2 \cdot 23 \cdot 79$	1.62
		8	$2^5 \cdot 3 \cdot 89 \ / \ 7 \cdot 31 \cdot 43$	1.21
		9	$29 \cdot 73 \ / \ 2^3 \cdot 17^2$	1.14
Saturn	Sidereal period:	1	$5 \cdot 17 \ / \ 41 \cdot 61$	2.83
	Synodic period:	1	$2^4 \cdot 151 \ / \ 41 \cdot 61$	80.3
		2	$7^2 \cdot 163 \ / \ 2^2 \cdot 3 \cdot 13 \cdot 53$	26.6
		3	$2 \cdot 3 \cdot 11 \cdot 59 \ / \ 29 \cdot 139$	5.19
		4	$41 \cdot 113 \ / \ 2^2 \cdot 11 \cdot 109$	4.06
		5	$3 \cdot 13 \cdot 43 \ / \ 2^3 \cdot 7 \cdot 31$	3.99
		6	$2^2 \cdot 17 \cdot 79 \ / \ 67 \cdot 83$	3.51
		7	$47 \cdot 127 \ / \ 37 \cdot 167$	2.88
		8	$2^6 \cdot 5 \cdot 31 \ / \ 3^2 \cdot 7 \cdot 163$	1.51
		9	$7 \cdot 7 \cdot 11^2 \ / \ 2^5 \cdot 137$	1.19
		10	$2^3 \cdot 19 \cdot 23 \ / \ 2 \cdot 7 \cdot 11 \cdot 47$	1.11
		11	$3 \cdot 31 \cdot 103 \ / \ 2^2 \cdot 37 \cdot 67$	1.03

Figure 7.7: Factorized synodic and sidereal orbital ratios for the superior planets, arranged according to their respective accuracy.

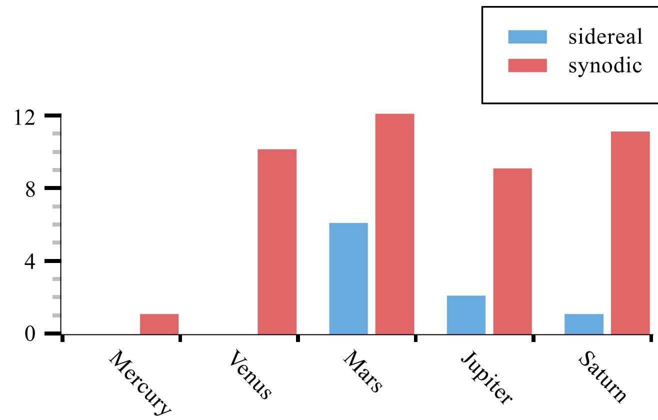


Figure 7.8: Diagram providing the number of factorization possibilities.

epicycle is equal to one anomalistic month. This fits the model of Hipparchus.

The duration of one sidereal month is 27.3217 days, and that of an anomalistic month is 27.5546 days (see Section 4.1). Nevertheless, the entire Lunar pin-and-slot mechanism in the Antikythera Mechanism is made up out of four 50-teeth gears. Implicitly, it equates both periods.

Since the periods of motion on the deferent and on the epicycle are not identical with any one of the periods used to represent the planets, we have to use more gears than the four additional ones of the Lunar pin-and-slot mechanism for the planets. The hypothetical pin-and-slot mechanism for Mercury illustrates this point.

Mercury's hypothetical pin-and-slot mechanism

Mercury moves on its deferent with the same speed as the Sun. One of the first approaches could very well be to connect it to the 224-teeth Sun Wheel, which obviously already rotates at the right speed. If we then look at the one possibility of factors for the ratio of Mercury $\nu_{☿} = 3 \cdot 13 \cdot 59 \ / \ 2 \cdot \ 5 \cdot 73$, we can calculate that our first set of gears must have sizes of 78, 59, 20, and 73 teeth.

Th tooth counts of 78 and 20 are obtained by $3 \cdot 13$ and $2 \cdot 5$ respectively, and which we then multiplied by an additional factor 2, since a gear of 10 teeth would probably be inconveniently small.

The gear train we are considering is propelled by the large Sun Wheel. When we look at the gears as normal fractions, it is obvious to see that when we multiply the entire train, we also have to balance for this factor. Therefore, we need a second 224-teeth gear wheel by which we can divide, and so balance our ratio.

With the gears found, we can compose our first gear train:

$$\textit{Mercury epicycle gear train} \ = \frac{224}{20} \times \frac{78}{73} \times \frac{59}{224} \ .$$

The final gear in this train, rotates with the same speed at which Mercury moves on its epicycle. The pin of the pin-and-slot mechanism should be placed on this gear (see Figure 7.3). Then, an identical gear train – though in reversed order – is needed to carry the motion back to the main axis of the Sun Wheel. The first gear of this train would then contain the slot of the pin-and-slot device.

The total gear train would then be parametrized by:

$$\textit{Mercury gear train} \ = \frac{224}{20} \times \frac{78}{73} \times \frac{59}{224} \tilde{\times} \frac{224}{59} \times \frac{73}{78} \times \frac{20}{224} \ .$$

This sort of gear train-design, would imply that the number of gears used for the total planetary extension would be far too great. The model of Mercury is one that needs relatively few gears, since its deferent is equal to the Mean Sun, and the synodic period can be obtained by only four gears. Still, the total gear train already requires eleven gears. This means that the total number of additional gears for all the planets would be more than 55.

Even without considering the fact that this total gear train would contain three additional 224-teeth gears, this design would be far too large to be useful. In a small device, especially as old and extraordinary like the Antikythera Mechanism, one would expect a more subtle and elegant design.

7.5 The bar design

In their articles, (Freeth, 2002b,a) and Wright (2002a,b, 2003, 2005b) propose another method for constructing the non-uniform epicycle gear trains. These ideas are part based on the small holes, pins and irregularities found on the surface of the Sun Wheel. Figure 7.9 shows the centre of Fragment A, along with its particular holes and pins.

Price (1974) already noted that the Sun Wheel could have had other parts attached to it. However, he did not manage to find an appropriate use for this.

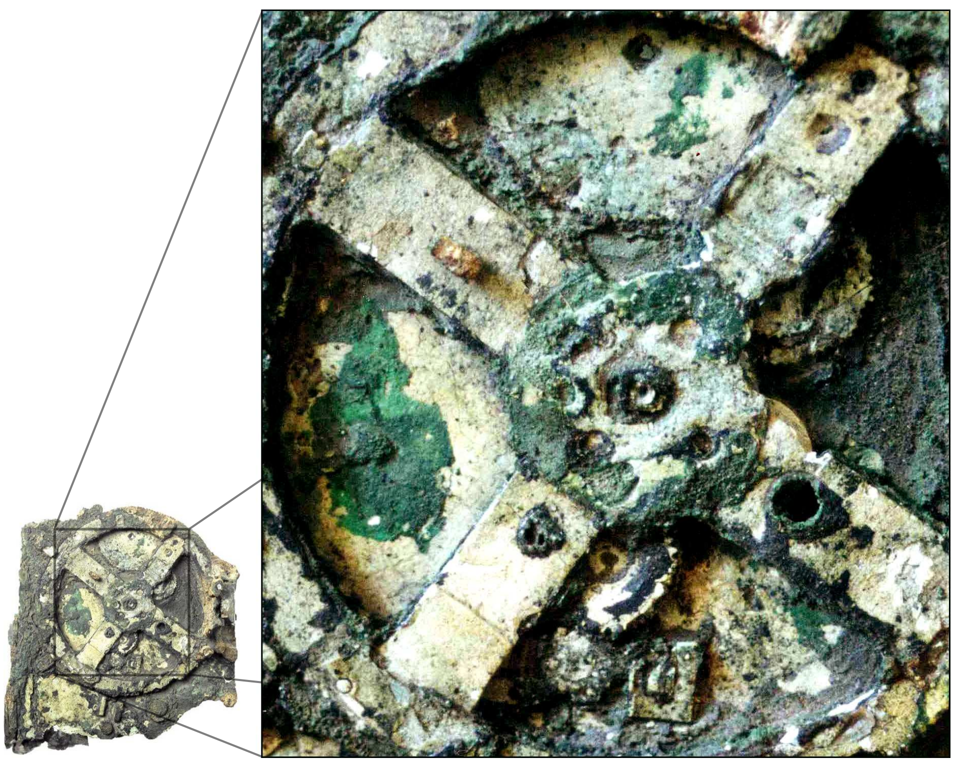


Figure 7.9: Outtake of Fragment A, illustrating the mounting possibilities present on the Sun Wheel. According to Wright (2002a), the square pipe at the centre, and the nuts and pins on the surrounding parts, could be interpreted as the remains of epicyclic gearing on top of the Sun Wheel.

Wright (2002a) takes this idea a step further, by proposing that the square pipe at the centre of the large Sun Wheel seen in Figure 7.9, and the nuts and pins on the surrounding parts, could be interpreted as the remains of *epicyclic gearing* on top of the Sun Wheel.

Concerning epicyclic gearing

Proposing a method of epicyclic gearing is a logical, as well as a bold one. Especially, since the name *epicyclic gearing* is a literal descendant from the first western clocks (Baillie et al., 1974; North, 2005) in which a gear system, that consists of one or more outer gears, revolves about a central gear (Lynwander, 1983). Figure 7.10 illustrates these basic principles. Another term used in present day gearing practices to indicate epicyclic gearing, is *planetary gearing.* The small outer gears that are part of the gear train, are referred to as *planet gears*, and the gear around which everything rotates, is referred to as the *Sun gear.* Needles to say, there is an overwhelming resemblance between the motion we want to represent, and the method we could use.

The manner by which we introduce epicyclic gearing, is by using the Sun wheel as a plateau whereon other gears are mounted. Similar to Wright (2002a), we thus introduce the idea that the small holes, pins and nuts on the Sun Wheel, clearly visible in Figure 7.9, may well be the remains of epicyclic gearing.

Figure 7.10 illustrates the basic principles of epicyclic gearing, as we aim to use it. The large gear serves as a plateau on which smaller gears rotate. By doing so, the large gear will be the drive for the motion of the centre of the epicycle on the deferent. The small gears on top represent the motion of the planet on its epicycle.

In most cases of epicyclic gearing, one of the basic components is held stationary. In our case, it is the first gear of the epicycle gear that will be at rest with respect to the Mechanism. The large gear which serves as the base for the epicycle gear train will rotate, and thus pull the epicycle gear train round the first stationary gear. In Figure 7.10, the red gear will thus be fixed, while the blue gear pulls the yellow epicycle gear round its stationary central gear. Therefore, the yellow

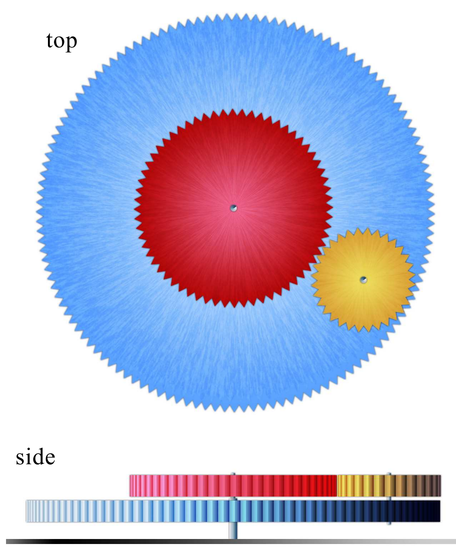


Figure 7.10: Top and side view illustrations of basic epicyclic gearing. The large gear serves as a plateau on which smaller gears rotate. Hereby, the motion of the centre of the epicycle could be represented by the large base gear, and the motion of the planet on its epicycle could be represented by the small gear.

gear is forced to rotate due to the inter-meshing gear teeth.

In the case of the inferior planets, the gear trains representing the epicycle motions are placed on the Sun Wheel. This is possible since the inferior planets share the same deferent; that of the Mean Sun. This hypothesis offers a direct explanation for the irregular features found on the Sun Wheel in Figure 7.9. For each of the three superior planets, other gears must provide the deferent motion.

Figure 7.18 illustrates this modular design, where the Sun Wheel propels three gear trains, which each drive another large 224-teeth base, intended to carry the three epicycle gear trains for the superior planets.

The pin distance

The final step of this setup, is to carry the motion of the epicycle gear trains back to the appropriate pointer on the outer dials. This is done by a bar that is connected to the central axis of the Sun Wheel, at one side. The other end of the bar is connected to a pin, attached to the last gear of the epicyclic gear train. Figure 7.11 illustrates this arrangement. Both by the motion of the deferent gear, as well as the epicycle gears, this bar design will result in pointers that represent the planets, along with their retrograde motions. The different pointers and bars will be connected through a series of concentric axes, centered on the axis b, as referred to in Figures 6.11 and 6.13.

The pin must be placed on the gear at the right distance from its axis, in order to describe the appropriate retrograde motion on the outer dials. To calculate this distance, let γ be the distance of the planet from the Sun, in astronomical units; one astronomical unit is defined as the average distance of the Earth from the Sun, $1\ AU = 149,597 \times 10^6\ m$ (de Pater and Lissauer, 2004). Let δ be the distance of the pin from the axis of the gear on which is rotates. And let χ be the distance between the central axis and the axis around which the pin revolves. Then, for an inferior planet, the distance we are looking for can be calculated by (Freeth, 2002a):

$$\textit{Inferior planet: } \delta = \gamma \cdot \chi\ . \tag{7.6}$$

For a superior planet the relation is somewhat different (Freeth, 2002a):

$$\textit{Superior planet: } \delta = \frac{\chi}{\gamma}\ . \tag{7.7}$$

Figure 7.11 illustrates the pin distance in epicyclic gearing. Shown are the same gears as in Figure 7.10, only outlined. The lines δ and χ represent the physical distances between the central axis and the axis of the final gear in the epicycle gear train, and the displacement of the pin on the last gear, respectively. Also indicated is their mutual relation with respect to the indication of the pointer.

In most cases, Equation 7.6 implies that the distance δ is larger than the size of the gear. Therefore, the pin is placed on a circular dish, attached to the same axis as the last gear. This has the additional benefit that it provides us with a manner for putting the pin at a certain height, making it possible for the bars to be placed well above the gears and gear trains. This is clearly illustrated in the schematic gearing diagrams of the epicycle gear trains for the planets, for instance Figure 7.12.

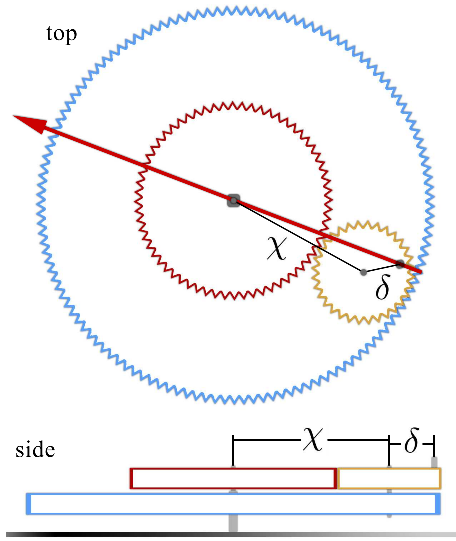


Figure 7.11: Illustration explaining the pin distance in epicyclic gearing. Shown are the same gears as in Figure 7.10, only outlined. The lines δ and χ represent the physical distances between the central axis and the axis of the final gear in the epicycle gear train, and the displacement of the pin on the last gear, respectively. Also indicated is their mutual relation with respect to the indication of the pointer.

7.6 Design of the planetary extension for the inferior planets

Now that we have the main ingredients for composing the planetary extension for the Antikythera Mechanism, the next step is to convert the ratio factors found in Section 7.3, along with the method of epicyclic gearing into a rational design. As shortly mentioned in the previous Section, the inferior planets will be mounted on top of the Sun Wheel. This solution will not do for the superior planets, since their epicycles travel on deferents with distinct velocities.

To manage with the three different deferents of the superior planets, we mount their large central gear wheels on separate modules. As mentioned in the previous Section, and illustrated in Figure 7.19, these modules will be placed between the Sun Wheel and the front dial. These three central gears will form the foundation for the epicycle gear trains of the three superior planets. However, before we outline the details of the modular extension, we will discuss the schematic design of the extensions of the Sun Wheel; the schematic design of the inferior planets.

Concerning the introduction of the bar

The use of a bar is not present in the contemporary reconstructions of the Antikythera Mechanism, therefore, a justification of this introduction is in place.

We feel confident to introduce this feature, since bars were used to transpose motion in many devices of antiquity. Singer et al. (1957a) describes several mechanisms, like water wheels and basic agricultural devices, in which a bar is connected to a pin on a wheel and a central axis. Also, many of the automatons made by Heron of Alexandria used this sort of transmission (Price, 1964). This leads us to believe, that such a manner of carrying motion would be known and available to the makers of the Antikythera Mechanism.

7.6.1 Selecting the appropriate factorizations

The table presented in Figure 7.5, provides in the factors that account for the synodic orbital ratios most accurately. Due to the introduction of two boundary conditions – an accuracy $\alpha > 10^6$, and no larger factor than 224 – this list is fairly short. In the case of Mercury, there is even only one set of factors left: $\nu_☿ = 3 \cdot 13 \cdot 59 \ / \ 2 \cdot \ 5 \cdot 73$. In the case of Venus, there are still ten possibilities. This is a positive fact, since it provides us with a certain scope in designing the gear trains. However, one may notice that the largest factor in eight of the ten possibilities is larger than 100. This may turn out to be a problem.

In our case of epicyclic gearing, the gear train resulting in the epicycle motion will be placed entirely on top of the deferent gear. This means that when we mount the inferior planets on top of the Sun Wheel, it becomes a problem when the epicycle gear train contains gears with the same shape and quality as the Sun Wheel. The design could easily present a ponderous mechanism, which simply will not fit inside the present reconstructions of the Antikythera Mechanism. Therefore, we introduce a third boundary condition, by posing that the gears that are part of the epicycle gear train, may not be larger than half the Sun Wheel. By making the simple assumption that the tooth count is proportional to the physical size of the gear, this means that the gears may not contain more than 112 teeth. This new boundary condition leaves us with two possibilities for Venus: $\nu_{♀,2} = 2 \cdot 37 \cdot 97 \ / \ 3^3 \cdot 5^2 \cdot 17$ and $\nu_{♀,4} = 2^3 \cdot 23 \cdot 47 \ / \ 5^2 \cdot 7 \cdot 79$.

7.6.2 Mercury

With the factors $\nu_☿$ found for Mercury, we can compose our first epicycle gear train:

$$\begin{aligned} \textit{Mercury epicycle gear train} &= \frac{b4}{Ma1} \times \frac{Ma2}{Mb1} \times \frac{Mb2}{Mc1} \\ &= \frac{32}{73} \times \frac{78}{20} \times \frac{59}{32} \ . \end{aligned}$$

Here we introduce a starting gear of 32 teeth, around which both the gear trains of Mercury and Venus are propelled.

Figure 7.12 shows the side view of the schematic gearing for the epicycle gear train for Mercury. Shown are the gears, their tooth counts, and their relative position. It is important to recognize that that this illustrated gear train is mounted on top of the rotating 224-teeth Sun Wheel. The 32-teeth starting gear will be stationary on an arbor, forcing the subsequent gears to rotate while they are being pulled round it.

The illustrated schematics of Figure 7.12 end in the circular dish on which a pin revolves. This pin is meant to lead the bar, which in turn is fixed to the axis of the Mercury pointer. The distance δ at which the pin has to be displaced from the centre on the circular dish can be calculated with the use of Equation 7.6. The distance of Mercury from the Sun is $\gamma_☿ = 0.387099 \ AU$ (de Pater and Lissauer, 2004). This means that the displacement distance for Mercury is given by:

$$\delta_☿ = 0.387099 \cdot \chi_☿ \ .$$

In most designs, this distance δ is larger than the physical size of the last gear of the epicycle gear train. Therefore, the pin will be placed on a circular dish, at a certain height. The circular dish will thus most likely be larger than the final 32-teeth gear of Figure 7.12

Figures 7.16 and 7.17 show the top view of a series of gearing diagrams, illustrating the build up of each of the separate layers of gears for the True Sun and the inferior planets, as mounted on the Sun Wheel. This series also contains the circular dish carrying the pin, the bar connected to the pin and the central axis and the relevant pointer.

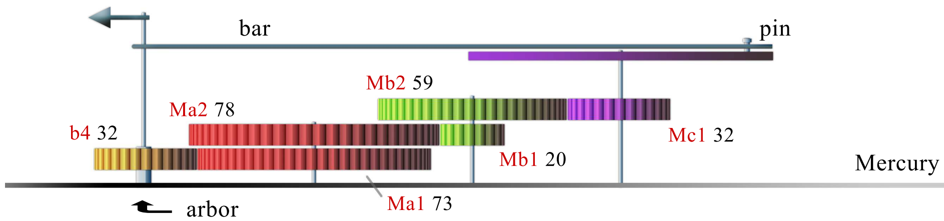


Figure 7.12: Side view of the schematic gearing diagram of the Mercury epicycle gear train, which is mounted on top of the rotating 224-teeth Sun Wheel. Shown are the gears, their tooth counts, and their relative position. The train begins with a fixed 32-teeth gear, and ends with a circular dish on which a pin is mounted. This pin pulls the bar along, which in turn leads the Mercury pointer around the dial.

7.6.3 Venus

Out of the two possible factorized synodic epicycle gear ratios found for Venus – $\nu_{♀,2}$ and $\nu_{♀,4}$ – we take the most accurate for our construction of the planetary extension. This set of factors can be converted into the following epicycle gear train:

$$\begin{aligned} \textit{Venus epicycle gear train} &= \frac{b4}{Va1} \times \frac{Va2}{Vb1} \times \frac{Vb2}{Vc1} \times \frac{Vc2}{Vd1} \\ &= \frac{32}{51} \times \frac{37}{20} \times \frac{30}{97} \times \frac{75}{32} \ . \end{aligned}$$

Like with Mercury's gear train, this epicycle gear train starts with the same 32-teeth gear that is fixed on an arbor.

Figure 7.13 illustrates a side view of the schematic gearing diagram for the epicycle gear train of Venus. Shown are the gears, their tooth counts and their relative position. This epicycle gear train is mounted on top of the Sun Wheel, along with the epicycle gear train of Mercury.

The distance δ at which the pin of the Venus epicycle gear train has to be displaced from the centre of its circular dish will be calculated with Equation 7.6. According to (de Pater and Lissauer, 2004), $\gamma_{♀} = 0.723332\ AU$. Thus, the displacement distance for Venus is given by:

$$\delta_{♀} = 0.723332 \cdot \chi_{♀} \ .$$

Like in the model for Mercury, this distance $\delta_{☿}$ will be larger than the actual size of the final 32-teeth gear as seen in Figure 7.13. The pin will therefore be placed on a circular dish.

A series of panels displaying the top view of the epicycle gear train for Venus is shown in Figures 7.16 and 7.17. The series illustrates the build up for each layer of gears, as mounted on the Sun Wheel. This series also contains the true Sun and Mercury, as well as all the circular dishes, pins, bars and relevant pointers.

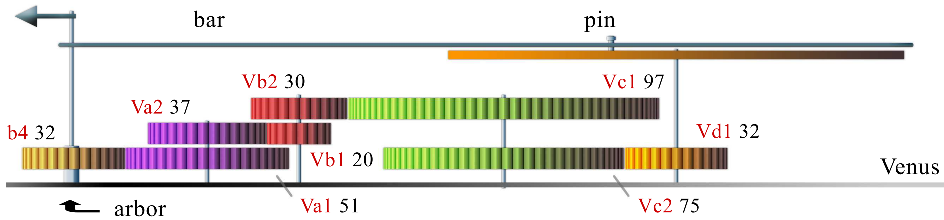


Figure 7.13: Side view of the schematic gearing diagram of the Venus epicycle gear train, which is mounted on top of the rotating 224-teeth Sun Wheel. Shown are the gears, their tooth counts, and their relative position. The train begins with a fixed 32-teeth gear, and ends with a circular dish on which a pin is mounted. This pin pulls the bar along, which in turn leads the Venus pointer around the dial.

7.6.4 The True Sun

One of the major benefits of modelling the planetary extension in this way, is that the incorporation of the model of the True Sun becomes almost trivial. As seen in Figure 5.3, the relation between the Mean Sun and the True Sun is quite rudimentary. The Sun rotates on its epicycle, while the centre of that rotates on a deferent; similar to the models of the planets. The reason why this model is so easy to combine, is due to the fact that the Sun cycles both his deferent and his epicycle in the period of one tropical year. The periods are equal.

The easiest way of representing the motion of the Sun, with the use of the same 32-teeth central gear as used in the models of Mercury and Venus, is by placing a similar 32-teeth gear right next to it. In that way, the periods would remain equal, and the gear train would be represented in the following way: $Solar\ epicycle\ gear\ train = 50/50$.

However, this construction is complicated to fulfil, since it would be the third separate gear train that is propelled by the same 32-teeth gear. It would prove difficult to assign the space to place this gear. Secondly, the distance of displacement δ will become to inaccurate in this design. In order to construe this last remark, let us first look at the distance of displacement for the Solar pin.

The distance of displacement for the Sun is calculated in a slightly different way, as for the planets. With the planets we are using the distance of the planet towards the Sun; γ. Since the projected eccentricity of the Sun is in fact – as we know now – a result of the eccentricity of the Earth, we are looking for the distance of the centre of the eccentric of the Earth's orbit. This is distinctly different from the philosophy of the ancient Greek. Therefore, we rely on the values found in classical times. According to Evans (1998), Ptolemy describes in his Almagest how Hipparchus found a Solar eccentricity of 0.0334, in units where the radius of the deferent is unity[1]. This value can be seen as an analogue to the planetary

[1] Hipparchus found the value for a Solar eccentricity of 0.0334 by measuring the exact lengths of the seasons, which are not equal. By comparing these periods to the circle of the Zodiac, Hipparchus was able to deduct the eccentricity, as well as the direction of the centre of the eccentricity on the celestial sphere (Pedersen, 1974; Evans, 1998).

distance γ used in Equation 7.6. Therefore, the distance of displacement for the Sun must be:

$$\delta_\odot = 0.0334 \cdot \chi_\odot \ .$$

This underlines, that it is not optimal to place the central axis and the axis on which the circular dish for the Solar pin is mounted, very close together. In order to construct a more accurate $\delta_\odot$, it is preferable to make $\chi_\odot$ large. This will yield a more precise deflection from the Sun pointer.

So, because we require the necessary space, and aim to assemble an accurate Sun pointer, we arrange an extended gear train for the representation of the Sun. This does, however, not imply that we need more gear in total. We can use the second 73-teeth gear in the epicycle gear train for Mercury. By designing it that way, the distance χ can be increased sufficiently, and there is enough space to place the gear, circular dish, pin and bar.

The resulting gear train can then be parametrized by the following expression:

$$\begin{aligned} \textit{True Sun epicycle gear train} &= \frac{b4}{Ma1} \times \frac{Ma1}{Ha1} \\ &= \frac{32}{73} \times \frac{73}{32} \ . \end{aligned}$$

It is easily seen that the total ratio of this Solar epicycle gear train is equal to 1. The input period of the Mean Sun is thus equal to the output period, that of the True Sun.

Figure 7.14 shows the side view of the schematic gearing for the epicycle gear train for the Sun, as mounted on top of the Sun Wheel. Shown are the gears, their tooth counts and their relative position. With the first two gears, it develops identical as the schematic diagram for the epicycle gear train of Mercury. The third and final gear propels a circular dish, on which the pin is mounted. This pin pulls the bar along, which in turn is the lead for the Sun pointer.

Figure 7.14: Side view of the schematic gearing diagram of the Solar epicycle gear train, as mounted on top of the rotating 224-teeth Sun Wheel. This design develops identical to the Mercury epicycle gear train (see Figure 7.12), to end with a circular dish on which a pin is mounted, which pulls the bar along. This leads the Sun pointer around the dial.

7.6.5 Arranging epicycle gear trains on the Sun Wheel

The table in Figure 7.15 lists all the gears that are introduced by the models for the inferior planets and the Sun. This shows that a total of 14 additional gears are needed to describe the planetary extension of the inferior planets for the Antikythera Mechanism.

The overall picture of the gear trains representing the inferior planets and the True Sun is represented as a top view in Figures 7.16 and 7.17. These two Figures enclose a series of 6 Sub-figures, in which the different layers of gears, dishes and bars are illustrated, as they are mounted on top of the Sun Wheel of Fragment A. The same color coding is maintained as in Figures 7.12, 7.13 and 7.14.

	Name	Axis	Tooth count	Rotation	Info
3	$b1$	b	224	↻	*Sun Wheel*
37	$b4$	b	32	↺	*fixed by arbor*
38	$Ma1$	Ma	73	↻	
39	$Ma2$	Ma	78	↻	
40	$Mc1$	Mc	20	↺	
41	$Mc2$	Mc	59	↺	
42	$Md1$	Md	32	↻	*Mercury*
43	$Va1$	Va	51	↻	
44	$Va2$	Va	37	↻	
45	$Vb1$	Vb	20	↺	
46	$Vb2$	Vb	30	↺	
47	$Vc1$	Vc	97	↻	
48	$Vc2$	Vc	75	↻	
49	$Vd1$	Vd	32	↺	*Venus*
50	$Ha1$	Ha	32	↺	*True Sun*

Figure 7.15: Table of observed (3) and hypothetical (37 to 50) gears in the planetary extension of the inferior planets for the Antikythera Mechanism. Given are the name of the gear, the axis of the gear and the tooth count for every gear. The newly introduced axes are denoted by capitals. The column entitled rotation shows an icon indicating the direction of rotation, as seen when looking through the front of the Mechanism. With this must be noted that 32-teeth gear 37 is fixed on an arbor, though, relative to the large Sun Wheel it rotates counterclockwise. The last column gives supplementary information.

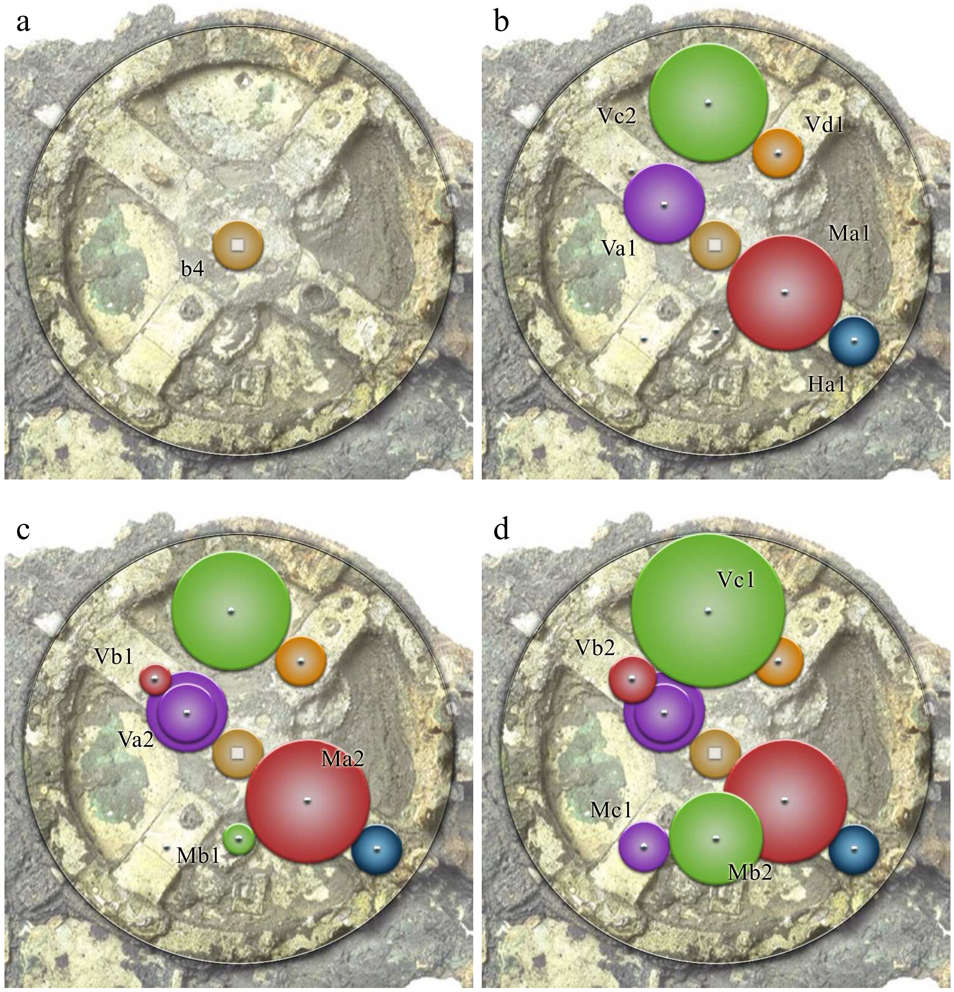
Shown in Sub-figure **a** of Figure 7.16, is the 32-teeth gear that is fixed on an arbor. Even though, this gear is stationary, the table lists its rotation as being counterclockwise. We have done so, because it is more insightful to consider the large base wheel as the stationary element, when examining the epicycle gear train. In the actual setting, the gears of the epicycle gear train rotate, while this entire gear train revolves around the central axis. By considering the large base wheel as the stationary part, one can follow the gears of the epicycle gear train, without their superimposed motion. However, when the base gear is regarded stationary, the otherwise stationary gear has to rotate in the opposite direction. Therefore, we consider the central 32-teeth gear as rotating counterclockwise.

Sub-figures **b** through **d** illustrate the three layers of gears as proposed in Figures 7.12, 7.13 and 7.14. Starting with the bottom layer in Sub-figure **b**, and ending with the third layer of gears in Sub-figure **d**. In Sub-figures **e**, the diagram is extended with the circular dishes and their mounted pins.

The final image is shown in Figure 7.17, where Sub-figure **f** illustrates the bars and pointers for the True Sun, Mercury and Venus.

7.7 Design of the planetary extension for the superior planets

Figure 7.17 illustrates the total epicyclic gearing model for the Sun and the inferior planets. Still, this is only the first of four planetary extension modules we find back in our hypothetical clockwork. Each of the three superior planets requires an extra separate platform construction of epicyclic gearing. It includes a large base gear, that reproduces the motion of the epicycle on its deferent. In turn, the epicycle gear train, representing the motion of the planet on its epicycle, is mounted on



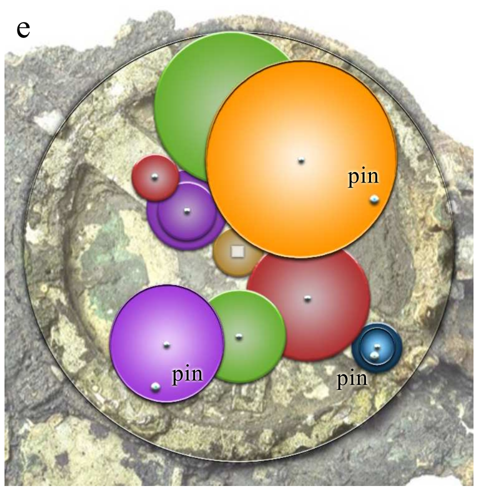


Figure 7.16: Top view of a series of schematic gearing diagrams – not to scale – of Fragment A and the inferior planets. Shown are the different layers of gears mounted on top of Fragment A, developing through sub-figures **a** to **f**, of which the latter is displayed in Figure 7.17. Sub-figure **a** starts with the fixed 32-teeth gear that propels all epicycle gear trains, mounted on the Sun Wheel, as proposed by Wright (2002a). Sub-figures **b** to **d** illustrate the three layers of gear as proposed in Figures 7.12, 7.13 and 7.14. Sub-figure **e** contains the circular dishes on which the pins are mounted.

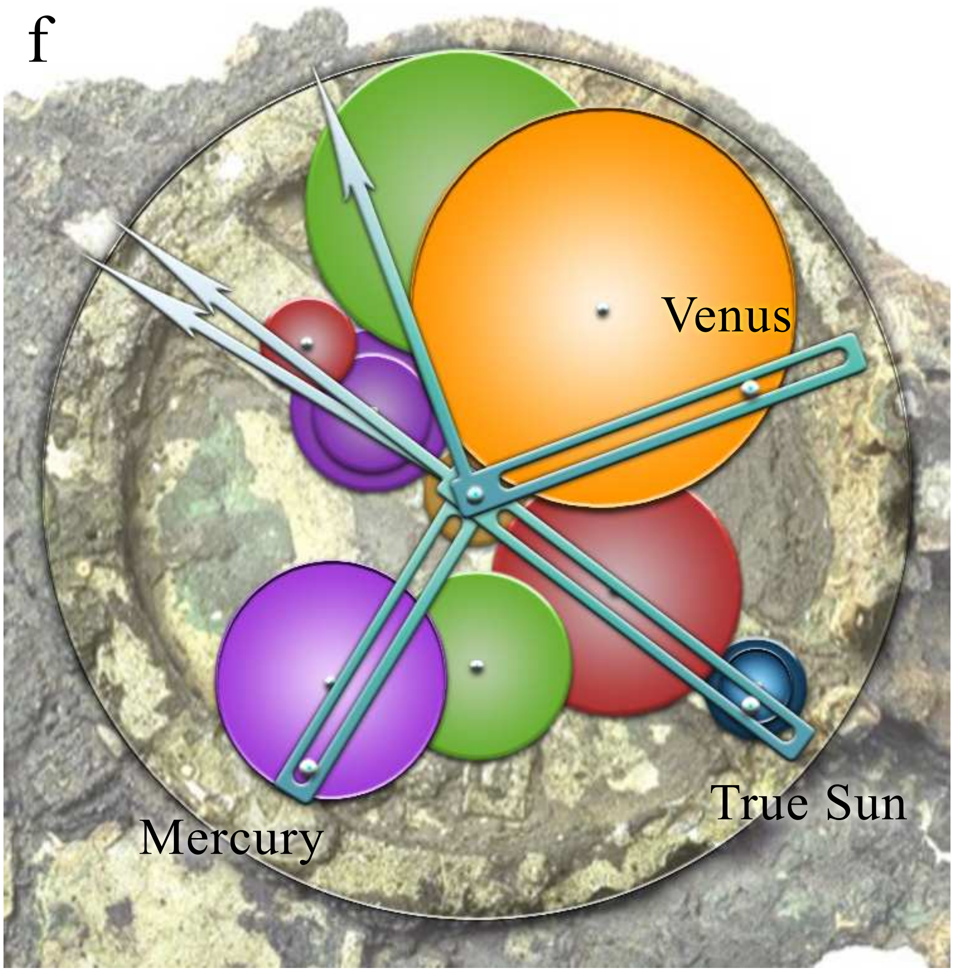


Figure 7.17: Top view of the schematic gearing diagram – not to scale – of Fragment A and the inferior planets. Shown are the different layers of gears mounted on top of Fragment A, as proposed in Figures 7.12, 7.13 and 7.14. This last image illustrates the bars and pointers of the True Sun, Mercury and Venus. *Continuation of Figure 7.16.*

top of this large base gear.

The base gears of the superior planets rotate with a period equal to their sidereal period. This motion is propelled by the Sun Wheel, through a series of gear trains that wrap around the modules, in the vacancies at the upper or lower side. Figure 7.18 illustrates this construction.

The gears that propel the three base gears for the superior planets are driven by the Sun Wheel. This implies that each gear train, driving the base gears, starts with a 224-teeth gear. This provides us with a reason to design the three base gears also as 224-teeth wheels, because in that way, the two large gears will cancel each other out when composing the gear trains. Subsequently, this supplies us with the largest possible base gears, which is beneficial since they are intended to act as a plateau for the epicycle gear trains. They therefore require the physical space on which the gears have to be mounted.

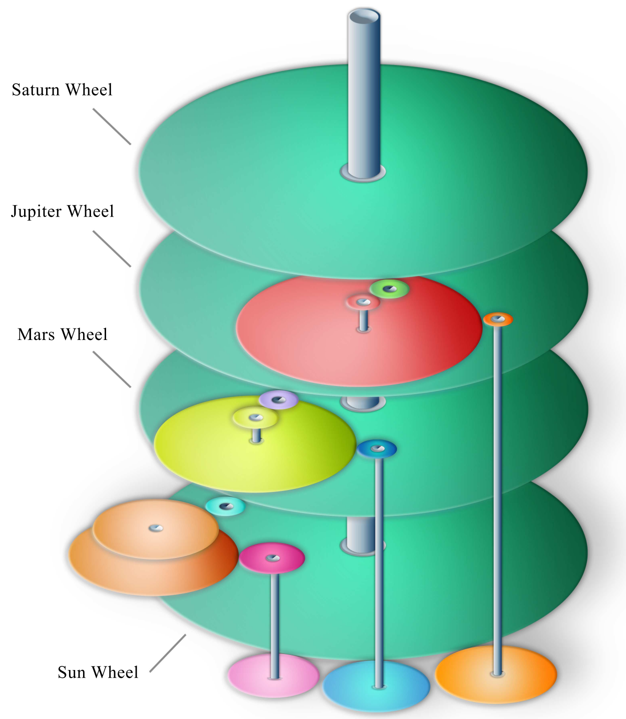


Figure 7.18: Inclined view of the planetary modules, as they are propelled by the Sun Wheel and subsequent sidereal orbital gearing. From the bottom up, the large green gears are the Sun Wheel, followed by the base gears for each of the three superior planet epicycle gear trains. The gear trains in front are responsible for propelling the large gears in the relevant sidereal orbital times. Used is the same design and color coding as in Figure 7.19.

7.7.1 Propelling the superior planet modules

The table of Figure 7.7 provides us with the factorized sidereal orbital ratios for the superior planets, given the fact that the accuracy $\alpha > 10^6$, and none of the factors are larger than 224. Amongst the various possibilities we will illustrate the most plausible one.

For Mars, this results in six separate possibilities. However, most of these possibilities contain factors much larger than 100. And since we are working towards an elegant design, able to fit within the margins of the Antikythera Mechanism, we use the second solution; $\nu_{♂,2} = 3^3 \cdot 7 \cdot 11 \;/\; 2 \cdot 5 \cdot 17 \cdot 23$.

Out of this ratio $\nu_{♂,2}$ and the condition that the gear train starts and ends with a 224-teeth gear, we can compose the following sidereal n for the module of Mars:

$$\begin{aligned} \textit{Mars sidereal gear train} &= \frac{b4}{Ca1} \times \frac{Ca2}{Cb1} \times \frac{Cb2}{Cc1} \times \frac{Cc1}{b5} \\ &= \frac{224}{46} \times \frac{33}{85} \times \frac{63}{\phi_{♂}} \times \frac{\phi_{♂}}{224}\,, \end{aligned}$$

where $\phi_{♂}$ is defined as a gear with an arbitrary number of teeth. This gear is necessary since the base gear has to rotate in the appropriate direction.

There are two possible factorized sidereal orbital ratios for Jupiter (see Figure 7.7). The first and most accurate possibility also accounts for the smallest factors; $\nu_{♃,1} = 2 \cdot 5 \cdot 23 \;/\; 3^3 \cdot 101$. With this, we compose the sidereal gear train for the second module of Jupiter:

$$\begin{aligned} \textit{Jupiter sidereal gear train} &= \frac{b4}{Cd1} \times \frac{Cd2}{Ce1} \times \frac{Ce2}{Cf1} \times \frac{Cf1}{b6} \\ &= \frac{224}{54} \times \frac{20}{101} \times \frac{23}{\phi_{♃}} \times \frac{\phi_{♃}}{224} \,. \end{aligned}$$

As with the sidereal gear train for Mars, $\phi_{♃}$ is defined as a gear with an arbitrary number of teeth. Note that the number of teeth on this gear may also differ from $\phi_{♂}$. The reason for introducing this gear is the same however; to make the base gear rotate in the appropriate direction.

The choice for a factorization of the sidereal gear ratio of Saturn is a trivial one, since there is only one option; $\nu_{♄} = 5 \cdot 17 \;/\; 41 \cdot 61$. The resulting sidereal gear

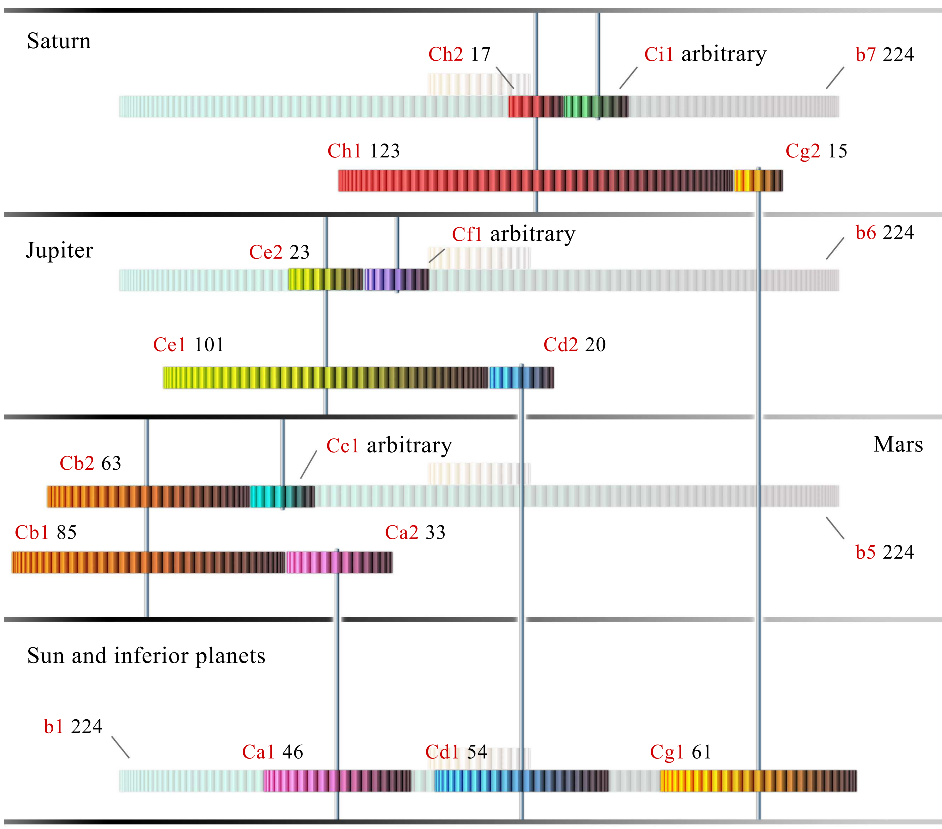


Figure 7.19: Side view of the schematic gearing diagram for the sidereal gear trains which propel the superior planetary modules. In the lower section, the Sun Wheel is shown. On this gear, the epicycles of the inferior planets and the Sun are mounted. In the three sections above the Sun Wheel, the large Mars, Jupiter and Saturn Wheels are presented. These three wheels are the cores of their subsequent superior planet modules. At the foreground, three gear trains are shown. These are responsible for the rotating the 224-teeth superior planet wheels in their different sidereal periods.

	Name	Axis	Tooth count	Rotation	Info
3	$b1$	b	224	↻	*Sun Wheel*
51	$Ca1$	Ca	46	↺	
52	$Ca2$	Ca	33	↺	
53	$Cb1$	Cb	85	↻	
54	$Cb1$	Cb	63	↻	
55	$Cc1$	Cc	–	↺	$\phi_{\mars}$ - *arbitrary*
56	$b5$	b	224	↻	*Mars Wheel*
57	$Cd1$	Cd	54	↺	
58	$Cd1$	Cd	20	↺	
59	$Ce1$	Ce	101	↻	
60	$Ce1$	Ce	23	↻	
61	$Cf1$	Cf	–	↺	$\phi_{\jupiter}$ - *arbitrary*
62	$b6$	b	224	↻	*Jupiter Wheel*
63	$Cg1$	Cg	61	↺	
64	$Cg1$	Cg	15	↺	
65	$Ch1$	Ch	123	↻	
66	$Ch2$	Ch	17	↻	
67	$Ci1$	Ci	–	↺	$\phi_{\saturn}$ - *arbitrary*
68	$b7$	b	224	↻	*Saturn Wheel*

Figure 7.20: Table of observed (3) and hypothetical (51 to 68) gears in the planetary extension of the superior planet modules for the Antikythera Mechanism. Given are the name of the gear, the axis of the gear and the tooth count for every gear. The newly introduced axes are denoted by capitals. The column entitled rotation shows an icon indicating the direction of rotation, as seen when looking through the front of the Mechanism. The last column gives supplementary information.

train for the module of Saturn is the following:

$$\begin{aligned} \textit{Saturn sidereal gear train} &= \frac{b4}{Cg1} \times \frac{Cg2}{Ch1} \times \frac{Ch2}{Ci1} \times \frac{Ci1}{b7} \\ &= \frac{224}{61} \times \frac{15}{123} \times \frac{17}{\phi_{\saturn}} \times \frac{\phi_{\saturn}}{224} \,, \end{aligned}$$

where $\phi_{\saturn}$ is defined similar, and because of the same reason, as for the two other superior planets. Still, $\phi_{\mars} \neq \phi_{\jupiter} \neq \phi_{\saturn}$.

Some of the gears in this arrangement for Saturn are quite small, however, further multiplications will cause the large gears to become too large. In fact, we may justify this on the ground that there are gears with less than 15 teeth in the reconstruction of the Antikythera Mechanism by Freeth et al. (2008).

A side view of the schematic gearing diagram of superior planet modules and their propelling gear trains is shown in Figure 7.19. At the bottom, the module of the Sun Wheel is shown. This is also the location where the epicycle gear trains for the True Sun and the inferior planets are located. In the foreground, the three sidereal gear trains are shown which lead to the first, second and third module, ones for Mars, Jupiter and Saturn.

The table of Figure 7.20 lists all the gears of superior planet modules for the Antikythera Mechanism. Along with their gear names, axis and tooth counts. This table shows also that a total of 18 gears are needed to propel the separate modules.

7.7.2 Mars

Now that we have our deferents in motion, the last step is to compose the epicycle gear trains for each of the superior planets. As we have seen in Section 7.2, the superior planets make one revolution on their epicycle in one synodic period, similar to the inferior planets. For Mars, the table of Figure 7.7 provides us with twelve different possibilities in which the synodic orbit can be factorized. We use the seventh one, $\nu_{♂,7} = 2 \cdot 31 \cdot 83 \ / \ 3^3 \cdot 11 \cdot 37$, since this set of factors allows us to construct a gear train with only three additional axes, and no gears larger than 111 teeth:

$$\begin{aligned} \textit{Mars epicycle gear train} &= \frac{b8}{Ra1} \times \frac{Ra2}{Rb1} \times \frac{Rb2}{Rc1} \\ &= \frac{32}{111} \times \frac{62}{99} \times \frac{83}{32} \ . \end{aligned}$$

Like the epicycle gear trains for the inferior planets, the gear trains for the superior planets commence with a stationary 32-teeth gear, fixed on an arbor. This entire epicycle gear train is mounted on top of the rotating 224-teeth Mars Wheel.

Figure 7.21 illustrates a side view of the schematic gearing diagram of the Mars epicycle gear train. Shown are the gears, their tooth counts, and their relative position. The gear train ends in a 32-teeth gear that propels the circular dish. As with the inferior planets, this dish contains a pin that pulls along a bar, which in turn leads the pointer for Mars.

The distance at which this pin has to be displaced from the centre of the dish, is given by Equation 7.7. From de Pater and Lissauer (2004), we know that $\gamma_{♂} = 1.52369 \ AU$. Therefore, the distance of displacement is given by:

$$\delta_{♂} = 1.52369^{-1} \cdot \chi_{♂} \ .$$

With this, the second module, and the first of a superior planet is accomplished.

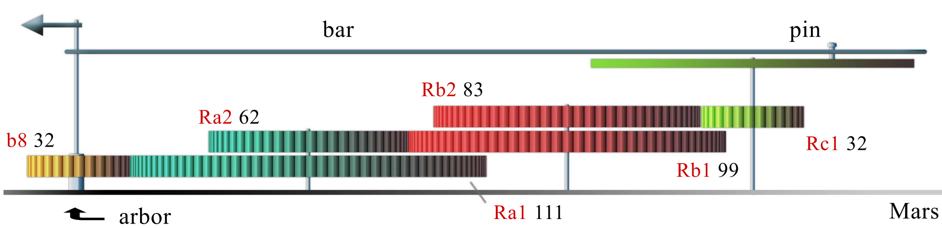


Figure 7.21: Side view of the schematic gearing diagram of the Mars epicycle gear train, which is mounted on top of the rotating 224-teeth Mars Wheel. Shown are the gears, their tooth counts, and their relative position. The train begins with a fixed 32-teeth gear, and ends with a circular dish on which a pin is mounted. This pin pulls the bar along, which in turn leads the Mars pointer around the dial.

7.7.3 Jupiter

Figure 7.7 gives nine different possibilities for a factorization of the synodic orbital ratio of Jupiter. Due to the fact that there is no possibility for a design with three axes and gears with less than 100 teeth, we compose a gear train with four axes and make use of the second possibility: $\nu_{♃,2} = 2^5 \cdot 5 \cdot 61 \;/\; 3 \cdot 11 \cdot 17 \cdot 19$. With these $\nu_{♃,2}$, we arrange the following epicycle gear train:

$$\begin{aligned} \textit{Jupiter epicycle gear train} &= \frac{b9}{Ja1} \times \frac{Ja2}{Jb1} \times \frac{Jb2}{Jc1} \times \frac{Jc2}{Jd1} \\ &= \frac{32}{32} \times \frac{61}{33} \times \frac{32}{38} \times \frac{20}{34} \,. \end{aligned}$$

Figure 7.22 illustrates a side view of the schematic gearing diagram, with the gears, their tooth counts, and their relative position, of the Jupiter epicycle gear train.

The initial 32-teeth gear is the stationary gear. And like the previous epicycle gear trains, the arrangement ends with a gear propelling a circular dish. On this dish, a pin is mounted that pulls a bar along, which in turn leads the Jupiter pointer.

Equation 7.7 gives the relation by which the displacement of the pin from the centre of the dish can be calculated. The distance of Jupiter from the Sun is $\gamma_{♃} = 5.20276\ AU$ (de Pater and Lissauer, 2004). Therefore, the distance of displacement must be:

$$\delta_{♃} = 5.20276^{-1} \cdot \chi_{♃} \,,$$

which in turn, provides us with the necessary data by which the third superior planet module can be put together.

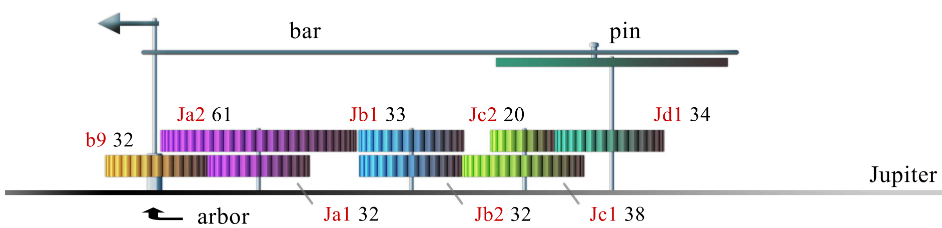


Figure 7.22: Side view of the schematic gearing diagram of the Jupiter epicycle gear train, which is mounted on top of the rotating 224-teeth Jupiter Wheel. Shown are the gears, their tooth counts, and their relative position. The train begins with a fixed 32-teeth gear, and ends with a circular dish on which a pin is mounted. This pin pulls the bar along, which in turn leads the Jupiter pointer around the dial.

7.7.4 Saturn

For the realization of the last module for the superior planet Saturn, the table of Figure 7.7 provides us with eleven different possibilities by which we can factorize the synodic orbital ratio of Jupiter. We use the fifth option; $\nu_{♄,2} = 3 \cdot 13 \cdot 43 \;/\; 2^3 \cdot 7 \cdot 31$, since this contains the smallest factors. Out of these factors, the following gear trains can be composed:

$$\begin{aligned} \textit{Saturn epicycle gear train} &= \frac{b10}{Sa1} \times \frac{Sa2}{Sb1} \times \frac{Sb2}{Sc1} \\ &= \frac{32}{56} \times \frac{43}{31} \times \frac{39}{32} \,. \end{aligned}$$

Figure 7.23 illustrates a side view of the schematic gearing diagram for the epicycle gear train of Saturn, as mounted on top of the rotating 224-teeth Saturn

Wheel, along with its gears, tooth counts and relative position. Like the models of the True Sun and the other four planets, the primary 32-teeth gear is the stationary component. And similarly, the gear train ends in a propelled circular dish. On top of this dish, the pin is mounted that pulls the bar along, which in turn leads the Saturn pointer.

The distance at which this pin must be displaced from the centre of the dish, can be calculated with the use of Equation 7.7. Where the distance of Saturn from the Sun is given by $\gamma_♄ = 9.54282\ AU$ (de Pater and Lissauer, 2004). The distance of displacement can then be indicated as following:

$$\delta_♄ = 9.54282^{-1} \cdot \chi_♄ \ .$$

This result is the last of the total number of schematic gearing diagrams, needed to describe the planetary extension for the Antikythera Mechanism. In the table of Figure 7.24, all gears are listed which are part of the gear trains of the epicycle gear trains for the superior planets.

For the epicycle gear trains, a total number of 19 gears must be introduced. Adding this to the total number of gears needed for the design of the True Sun, the inferior planets, and the drive for the superior planet modules, we introduce a total number of 52 gears for the planetary extension.

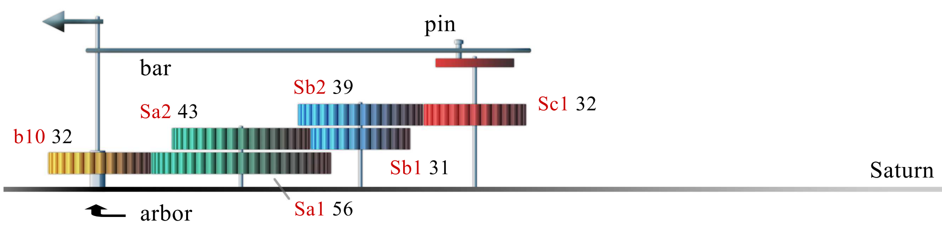


Figure 7.23: Side view of the schematic gearing diagram for the epicycle gear train of Saturn, as mounted on top of the rotating 224-teeth Saturn Wheel. Shown are the gears, their tooth counts, and their relative position. The train begins with a fixed 32-teeth gear, and ends with a circular dish on which a pin is mounted. This pin pulls the bar along, which in turn leads the Saturn pointer around the dial.

7.8 Alternate designs of the planetary extension

The schematic gearing diagrams shown in the previous two Sections, are designed using the factorized ratios of the tables in Figures 7.5 and 7.7 that seemed most plausible to use. The arguments we used to make our choice however, were mostly based on the fact that we wanted to use small gears or a minimal number of axes.

There is no such occurrence, that the one option would give a better result as the other. There is the difference in accuracy, though all of the presented factorizations have an accuracy $\alpha > 10^6$, which means that even the least accurate options would only be off 1 degree in 2777 years. Thus, other designs, as given in Section 7.3, are well possible.

One deviation worth investigating, is that of minimizing the total number of gears. As summarized in the previous section, we would need a total of 52 gears to realize our designs. This is a relative small number, if one supports the point of view that it reproduces the motions of the Sun and all the planets on their

	Name	Axis	Tooth count	Rotation	Info
69	*b*8	*b*	32	↺	*fixed by arbor*
70	*Ra*1	*Ra*	111	↻	
71	*Ra*2	*Ra*	62	↻	
72	*Rb*1	*Rb*	99	↺	
73	*Rb*2	*Rb*	83	↺	
74	*Rc*1	*Rc*	32	↻	*Mars*
75	*b*9	*b*	32	↺	*fixed by arbor*
76	*Ja*1	*Ja*	32	↺	
77	*Ja*1	*Ja*	61	↺	
78	*Jb*1	*Jb*	33	↺	
79	*Jb*1	*Jb*	32	↺	
80	*Jc*1	*Jc*	38	↺	
81	*Jc*1	*Jc*	20	↺	
82	*Jd*1	*Jd*	34	↺	*Jupiter*
83	*b*10	*b*	32	↺	*fixed by arbor*
84	*Sa*1	*Sa*	56	↻	
85	*Sa*2	*Sa*	43	↻	
86	*Sb*1	*Sb*	31	↺	
87	*Sb*2	*Sb*	39	↺	
88	*Sc*1	*Sc*	32	↻	*Saturn*

Figure 7.24: Table of hypothetical gears in the planetary extension of the superior planet modules for the Antikythera Mechanism. Given are the name of the gear, the axis of the gear and the tooth count for every gear. The newly introduced axes are denoted by capitals. The column entitled rotation shows an icon indicating the direction of rotation, as seen when looking through the front of the Mechanism. With this must be noted that 32-teeth gears 69, 75 and 83 are fixed on an arbor, though, relative to the large Sun Wheel it rotates counterclockwise. The last column gives supplementary information.

deferents and epicycles. However, the total number of gears in the contemporary model of the Antikythera Mechanism by Freeth et al. (2008), contains only 36 gears. Compared to that, the additional 52 gears would be substantial.

Optimising the modular gear trains

The planetary extension we designed, contains several gears which could be disposed of. These are gears that have been added in order to extend the symmetry and aesthetics of the design, and to prevent large peculiarities.

The latter occurs at the arrangement of the sidereal gear trains, propelling the large base gears on which the epicycle gear trains for the superior planet are mounted. As one can see in Figures 7.19 and 7.18, there are three gears introduced to invert the direction of rotation; gears $Cc1$, $Cf1$ and $Ci1$ (see the table of Figure 7.15). We have chosen for this configuration, since it requires small gears which are relatively easy to incorporate. We have situated them at the end of each gear train on our design, while they could also be put at the beginning, or between any inter-meshing set of gears in the train. However, it involves in total three gears, doing identical work.

Another solution would be to substitute the three gears, by one placed at the beginning of the three sidereal gear trains; between the Sun Wheel and the second gear of each train. This gear would have to propel three gear trains at once, thus it would have to be a large gear. The size – and with that the number of teeth – becomes important, since the three inter-meshing gears need the physical space to rotate beside is. Because of this, it could easily become a problem to carry the rotation back to the three base wheels of Mars, Jupiter and Saturn. After all, the remaining, and relative small gears would all need to fold back towards the central gears. Another argument against this solution, is the space available inside the Antikythera Mechanism; it would also be a challenge to fit relatively large gears besides the 224-teeth Sun Wheel. In all, it would make a difference of two gears.

Optimising the epicycle gear trains

The greatest progress in minimizing the total number of gears, can be made in optimizing the epicycle gear trains. On the basis of symmetry and aesthetic considerations of the design, we started each epicycle gear train with an identical fixed 32-teeth gear: namely $b4$, $b5$, $b6$ and $b7$.

When we choose to abandon this architectural preference, it would make a difference of nine gears. In each epicycle gear train two 32-teeth gears would cancel out. However, the epicycle gear trains of Mercury and Venus commence with the same gear, which means that only three 32-teeth gears will drop out. For the superior planets, it will differ six gears. Making it nine in total.

The resulting gear trains can be parametrized by the following expressions:

$$
\begin{aligned}
\textit{Mercury epicycle gear train} &= \frac{b4}{Ma1} \times \frac{Ma2}{Mb1} \\
&= \frac{78}{20} \times \frac{59}{73}\,, \\
\textit{Venus epicycle gear train} &= \frac{b11}{Va1} \times \frac{Va2}{Vb1} \times \frac{Vb2}{Vc1} \\
&= \frac{75}{20} \times \frac{37}{51} \times \frac{30}{97}\,, \\
\textit{Mars epicycle gear train} &= \frac{b8}{Ra1} \times \frac{Ra2}{Rb1} \\
&= \frac{62}{111} \times \frac{83}{99}, \\
\textit{Jupiter epicycle gear train} &= \frac{b9}{Ja1} \times \frac{Ja2}{Jb1} \times \frac{Jb2}{Jc1} \\
&= \frac{61}{38} \times \frac{32}{33} \times \frac{20}{34}\,, \\
\textit{Saturn epicycle gear train} &= \frac{b10}{Sa1} \times \frac{Sa2}{Sb1} \\
&= \frac{39}{56} \times \frac{43}{31}\,.
\end{aligned}
$$

Since the epicycle gear train for Mercury will change, the model for the True Sun is affected to. Within the model represented in Figure 7.14, the True Sun epicycle gear train starts with the same two gears as the Mercury epicycle gear train. In order to account for this, the new gear train of the True Sun is parametrized by:

$$
\begin{aligned}
\textit{True Sun epicycle gear train} &= \frac{b4}{Ma1} \times \frac{Ma1}{Ha1} \\
&= \frac{78}{20} \times \frac{20}{78}\,,
\end{aligned}
$$

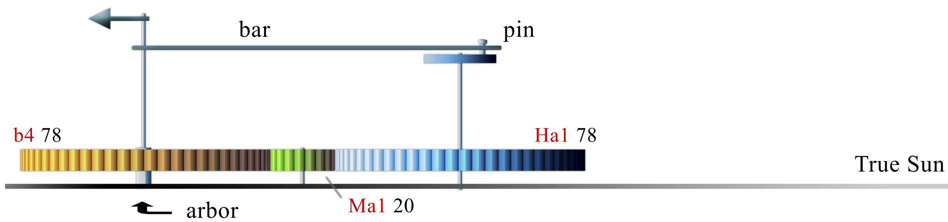


Figure 7.25: Side view of the optimized gearing schematic diagram of the True Sun epicycle gear train, starting with same two gears as the optimized model for Mercury, and ending in a 75-teeth gear. Further properties are equal to Figure 7.13.

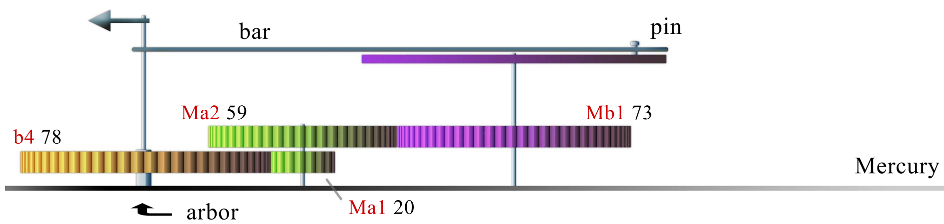


Figure 7.26: Side view of the optimized gearing schematic diagram of the Mercury epicycle gear train, starting with a 78-teeth fixed gear instead of a 32-teeth gear. Further properties are equal to Figure 7.12.

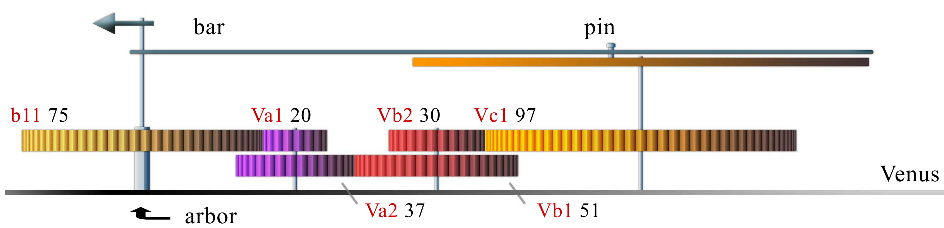


Figure 7.27: Side view of the optimized gearing schematic diagram of the Venus epicycle gear train, starting with a 83-teeth fixed gear instead of a 32-teeth gear. Further properties are equal to Figure 7.13.

making it still possible for the True Sun epicycle gear train, to begin with the same two gears as the model for Mercury.

Figures 7.26 through 7.30 illustrate the gearing schematics, when we choose to abandon the condition that the epicycle gear trains are required to commence with identical fixed gears. It shows the arrangements for the epicycle gear trains, using nine gears less.

On the numerous possibilities

Considering the changes proposed in this Section, it is possible to construct the planetary extension with only 40 gears, instead of the 52 gears stated previously. But even then, there are ways to further minimize the number of gears; the epicycle gear trains for Venus and Jupiter occupy three axes, instead of two. By using larger gears, with more than 112 teeth, we could compose epicycle gear trains containing

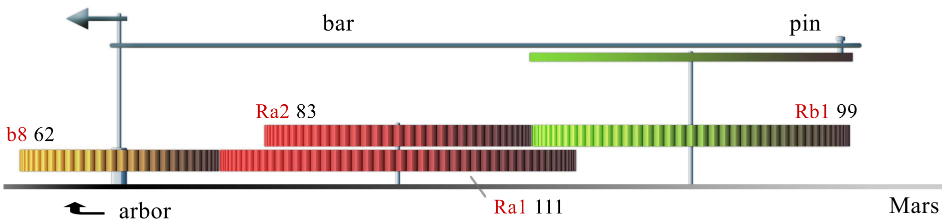


Figure 7.28: Side view of the optimized gearing schematic diagram of the Mars epicycle gear train, starting with a 62-teeth fixed gear instead of a 32-teeth gear. Further properties are equal to Figure 7.21.

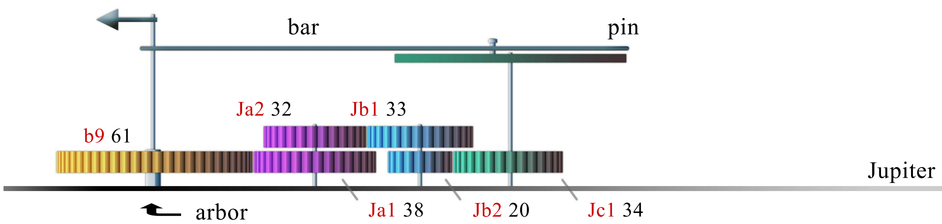


Figure 7.29: Side view of the optimized gearing schematic diagram of the Jupiter epicycle gear train, starting with a 61-teeth fixed gear instead of a 32-teeth gear. Further properties are equal to Figure 7.22.

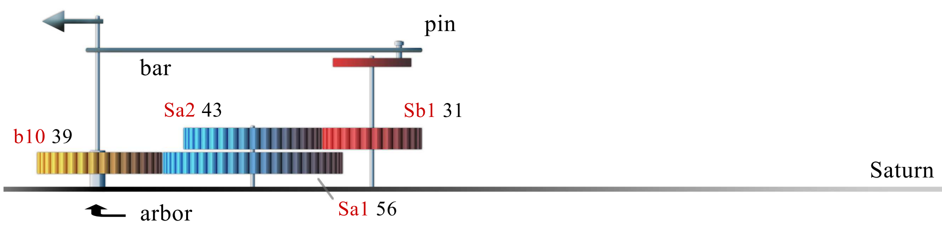


Figure 7.30: Side view of the optimized gearing schematic diagram of the Saturn epicycle gear train, starting with a 39-teeth fixed gear instead of a 32-teeth gear. Further properties are equal to Figure 7.23.

four gears also for these two planets. With that the total number of gears would be brought back to 36.

However, this truly undermines the design of the overall model. It is disputable which model is to be preferred, and of minor importance in this context. The important conclusion is the fact that it is possible to create a planetary extension for the Antikythera Mechanism, with approximately the same number of gears as used in the contemporary reconstructions of the ancient device. Thus making it possible, to turn the Antikythera Mechanism into a full-fledged planetarium with roughly twice the number of gears used in the present model.

Chapter 8

Conclusions & discussion

The Antikythera Mechanism is of crucial importance for the history of science and technology. It tells us of a revolution in human thought in ancient Greece, and is the earliest known example of a machine for making calculations. It is, by far, the earliest known machine predicting the future. The device presents us with the evidence for a technological sophistication in antiquity, which the modern world – till a couple of decades ago – never deemed possible.

8.1 Conclusions of the results

In Chapter 1, we formulate the central research question of this study, which inquires whether it is possible for the Antikythera Mechanism to reproduce the motions of the five planets, known by the ancient Greek. And if so, how such a design may have been arranged.

By now, we can confirm with a fair amount of certainty, that the planets could have been part of the Antikythera Mechanism. That is, we can confirm that it is possible that the device contained the planetary gear trains, propelling the relevant pointers for the planets.

Since we do not know in what shape the device was, when the Roman Merchant ship perished more than two millennia ago, we can never say whether it was a full pledged planetarium at that time. Nonetheless, various indications imply that planetaria did exist, and the Antikythera Mechanism is the best candidate available.

After describing extensive background research concerning the discovery and research of the fragments of the Antikythera Mechanism, and the astronomical and technological skills of the ancient Greek in Chapters 2, 3 and 4, we examined and computed simulations of different epicycle models held by in the Hellenistic era. We compared these models with the found fragments and the reconstructed models, and deducted a coherent model for the planets.

In Chapter 7, we describe our design for the planetary extension of the Mechanism. We present the different possibilities by which the planetary motions can be reproduced, and offer two series schematic diagrams in which we elaborate on different lines of architectural reasoning.

It forms the principal ground on which we conclude that there are several configurations in which the planets can be incorporated in the extended Antikythera Mechanism.

8.2 Discussion of the results

Relying on schematics

The models for our schematic gearing diagrams are far from definite. For instance, we assume a linear relation between the size of the gears and their tooth counts. As can be seen in Freeth et al. (2006), the gears found in the surviving fragments roughly agree to this relation. However, a deviation of this relation could very well be necessary when a physical model is to be constructed.

It takes the competence of a real craftsman, to recreate the planetary extension. We can not elaborate too deeply about the various properties of the gears; for instance their thickness, or their metallic alloy. We have not said anything about the shape of the gear teeth. As Bromley (1990b) notices, plain triangular gear teeth will probably be responsible for very rough action, and could even lock the entire gear train. He therefore proposes a model with rounded teeth.

Nonetheless, we are quite confident that this model works. There are a few working reconstructions of the Antikythera Mechanism, made by Wright (2002a) and the Dutch craftsman Tatjana van Vark[1]. Both do contain the planets and are based on the same modular construction.

We, as supposed to the manufacturers of the other planetary extensions for the Antikythera Mechanism, provide with the statistics and schematic diagrams out of which the design is assembled; leaving the construction of the actual device for future work.

For our design, we have tried to use only techniques and mechanisms that were recognized in the actual Antikythera Mechanism. Still, we were forced to introduce two techniques, since the alternatives seemed less favourable. The subjects of interest are the modular construction, as well as the use of the pin and bar, in leading the pointers across the outer dials. The alternative was a design using the same pin-and-slot mechanism as observed in the representation of the Lunar pointer. As described in Section 7.4, a design using this method would result in a architecture of multiple long gear trains, clearly less elegant and feasible as the modular solution. This led u to choose for the latter.

We also had to introduce the use of a bar. This was necessary in order to carry the motion of the last epicycle gear back to the central axis. Even though, the use of such a bar is not present in the contemporary reconstructions of the Antikythera Mechanism, we feel confident to introduce this feature, since bars were used to transpose motion in many devices of antiquity. Singer et al. (1957a) describes several mechanisms, like water wheels and basic agricultural devices, in which a bar is connected to a pin on a wheel and a central axis. Also, many of the automatons made by Heron of Alexandria used this sort of transmission (Price, 1964). This leads us to believe, that such a manner of carrying motion would be known and available to the makers of the Antikythera Mechanism.

[1] *http://www.tatjavanvark.nl/antikythera/*

Did the planets exist in the Antikythera Mechanism?

Up till now, we have discussed our method of reproducing the motions of the planets. A more underlying question is whether the planets were actually part of the device. We already discussed our stance that they could have fitted inside the mechanism. Still, we do not know the actual purpose and aspiration for which the Antikythera Mechanism was made. So, what was it for? Edmunds et al. (2006) provides in a listing of six possibilities:

1. It was a device for performing calendrical calculations.
2. It was a device for performing calendrical and astronomical calculations.
3. It was a tellurium[2].
4. It was a planetarium, displaying the relation of the Earth, Sun, Moon and planets.
5. It was a navigational instrument.
6. It was a device for performing astrological calculations.

The fifth of these can probably be dismissed right away. It is true that the artifact was found in a shipwreck, so were many other high status artifacts like the sculptures and amphorae. Furthermore, there is no obvious way in which the mechanism could have performed a navigational function.

The last option is harder to dismiss. One would expect more astrological references in the inscriptions, but as Swerdlow (1998) notes, most astronomers in ancient times, up until the nineteenth century, were also astrologers.

There is no definite answer, picking one of the six possible uses for the Antikythera Mechanism. However, we can say, that if the device had a purpose which included the motions of the planets, these could be incorporated in a relatively clear and obvious way.

8.3 Future work

Involving the turner's lathe

When philosophising about the continuation of this research, the obvious next step requires a further transformation of the schematic gearing diagrams, to the physical model. This could be with the realization of a concrete extended Antikythera Mechanism; containing the actual pointers for the five planets and the True Sun. Another option could be a 3D computer model, where one could virtually see all the working features.

The Dark Matter of ancient technological sophistication

The former British prime-minister and historian, Sir Winston Churchill, once said: *"History with its flickering lamp stumbles along the trail of the past, trying to reconstruct its scenes, to revive its echoes, and kindle with pale gleams the passion*

[2] A tellurium is a device for representing the relation of the Earth, Moon and Sun. This can be used for display or educational purposes.

of former days" (Edmunds et al., 2006). These words reflect our own reaction to the unique Antikythera Mechanism. Past attempts to understand its purpose are by now quite well documented, yet its profound significance is still not widely recognized among astronomers, classicists and historians of ideas and technology.

In many ways, the discovery of a mechanism like the Antikythera Mechanism, and the recognition of its profound implications on our thoughts of ancient technical sophistication, is kindred to the present-day search for dark matter in astronomy. It is similar, since both disciplines are unable to see the actual entity they want to examine. Both areas are condemned to investigate secondary phenomena, in order to deduce features inherent to their subject of interest.

The Mechanism constitutes an important indication for a level of technological knowledge, that has been undreamed-of in modern assumptions about the ancient Greek and Greco-Roman world. It must be seen as a crucial fingerprint, exposing a level of sophistication that had been invisible throughout the other windows on the ancient times.

It is in this respect, that the Mechanism is a physical artifact of almost tangible power, more complicated than any known device for a thousand years after its construction, forcing us to confront its implications for the development of human thought and technology.

It would be tremendously important, if a second Antikythera Mechanism would be dug up somewhere. If that device uncovered complementary knowledge about the device and its time. After all, almost everyone who has studied the mechanism agrees it could not be a one-off.

It has been observed that on close examination of the mechanism there is no evidence of any mistakes. All the mechanical features have a purpose. There are no extra holes, or bits of metalwork to suggest that the manufacturer modified his design as he built the mechanism. This leads to the conclusion that he must have built a number of predecessors. It would have taken practice, perhaps over several generations, to achieve this level of expertise (Marchant, 2006).

The evolution of technology

Research on the Antikythera Mechanism can have exceptional implications for our understanding of the advancements in technology. It is still a popular notion among scientists thinking about the history of their disciplines, that technological development is a simple progression; that there is a linear dependence in the evolution of technology. But as Marchant (2006) notes, history is full of surprises.

Technological knowledge can get lost, and there is no linear progression by which knowledge evolves. Maybe, some late descendant of the Antikythera Mechanism influenced the makers of the now called London Byzantine Sundial-Calendar described by Field and Wright (1985), or even the makers of the medieval European and Arab astrolabes. Even more speculative is the idea that descendants of the Antikythera Mechanism were taken to Byzantium. Only to be returned from the eastern to the western world, for instance during the crusades of the turbulent thirteenth century. Would this not explain the sudden birth of western clocks resembling the Antikythera Mechanism?

Nevertheless, it is even more obvious that much of the mind-boggling technological sophistication available in some parts of the Hellenistic and Greco-Roman world was simply not transmitted further, after the collapse of the Roman empire.

By examining the Antikythera Mechanism, we can recover pieces of the path of technological advancement. We can shed a light on some of the dark and forgotten realms of history. Realms so phenomenal and intriguing, like no one could have ever imagined.

APPENDIX A

Images and illustrations

A.1 The Fragments

Fragment A

This Section contains a large series of photographs, made of the three largest surviving fragments of the Antikythera Mechanism: Fragments A, B and C. The pictures were taken in the National Archaeological Museum of Athens, by Rien van de Weijgaert in September 2002.

Figure A.1: Photograph showing Fragments A, B and C, as displayed in the National Archaeological Museum of Athens.

Figure A.2: Front and side view of Fragment A. The side view clearly shows the irregular attachment where the drive gear and lever were attached. These were used to drive the other gears of the mechanism.

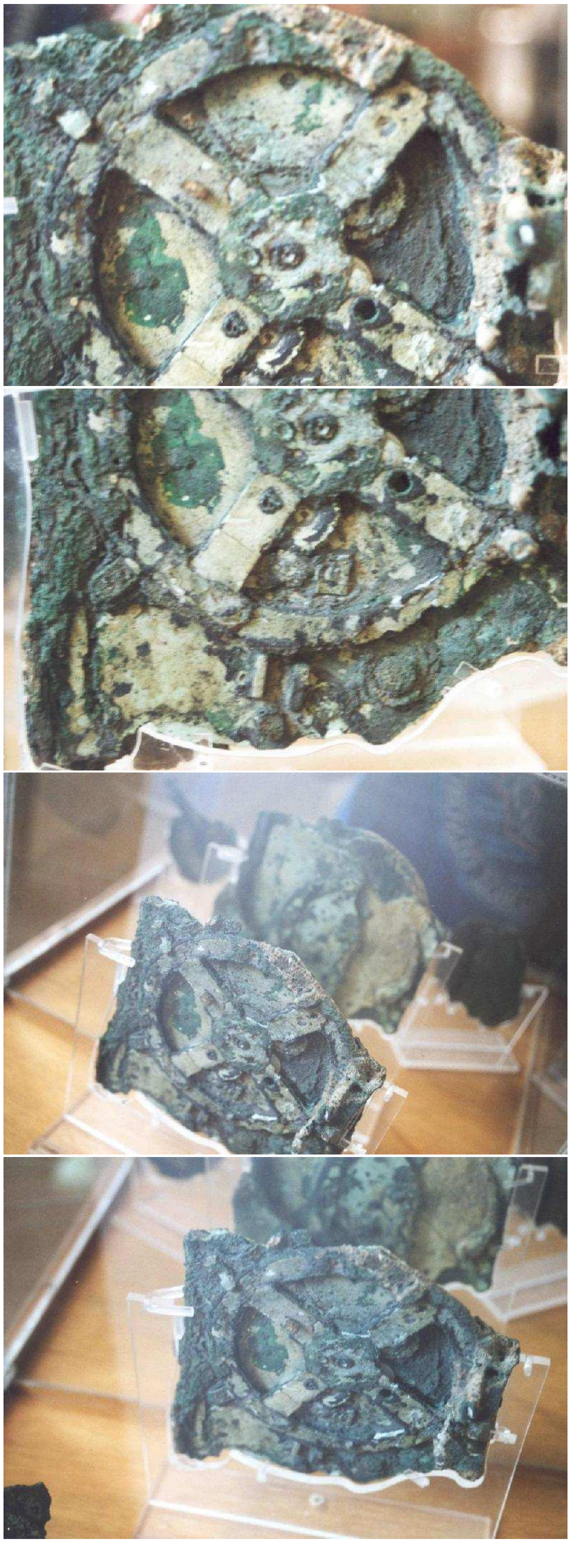


Figure A.3: Front and inclined top views of Fragment A, illustrating the various details of the artifact.

Figure A.4: Inclined side views of front and back of Fragment A. The images clearly illustrate the minuscule teeth belonging to the gears.

Fragment B

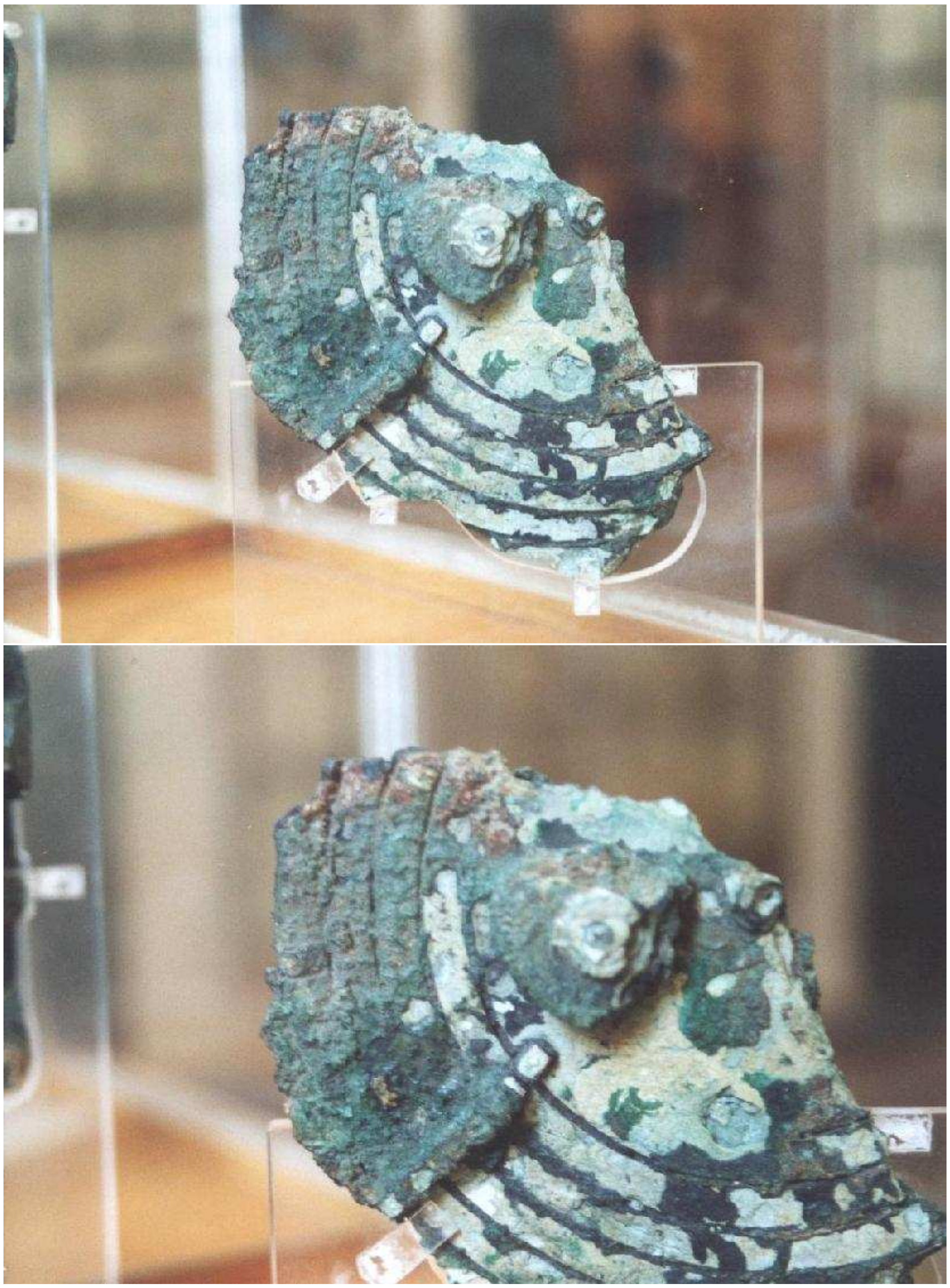


Figure A.5: Two front views of Fragment B, illustrating the partial gear and dial.

Fragment C

Figure A.6: Front and side view of Fragment C, illustrating the partial dial and inscriptions.

A.2 Rotating Fragment A

X-ray micro-focus computed tomography (CT) imaging

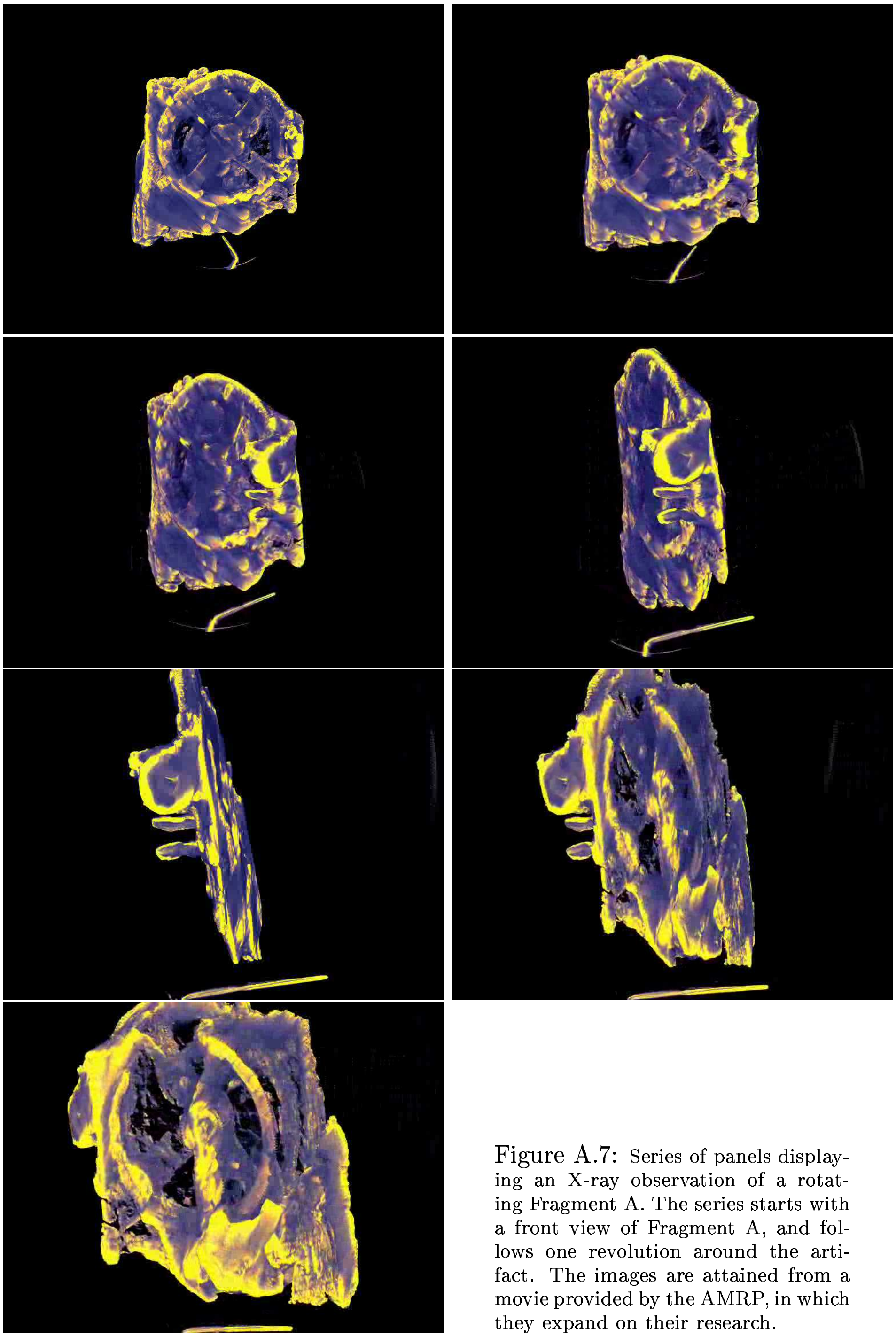
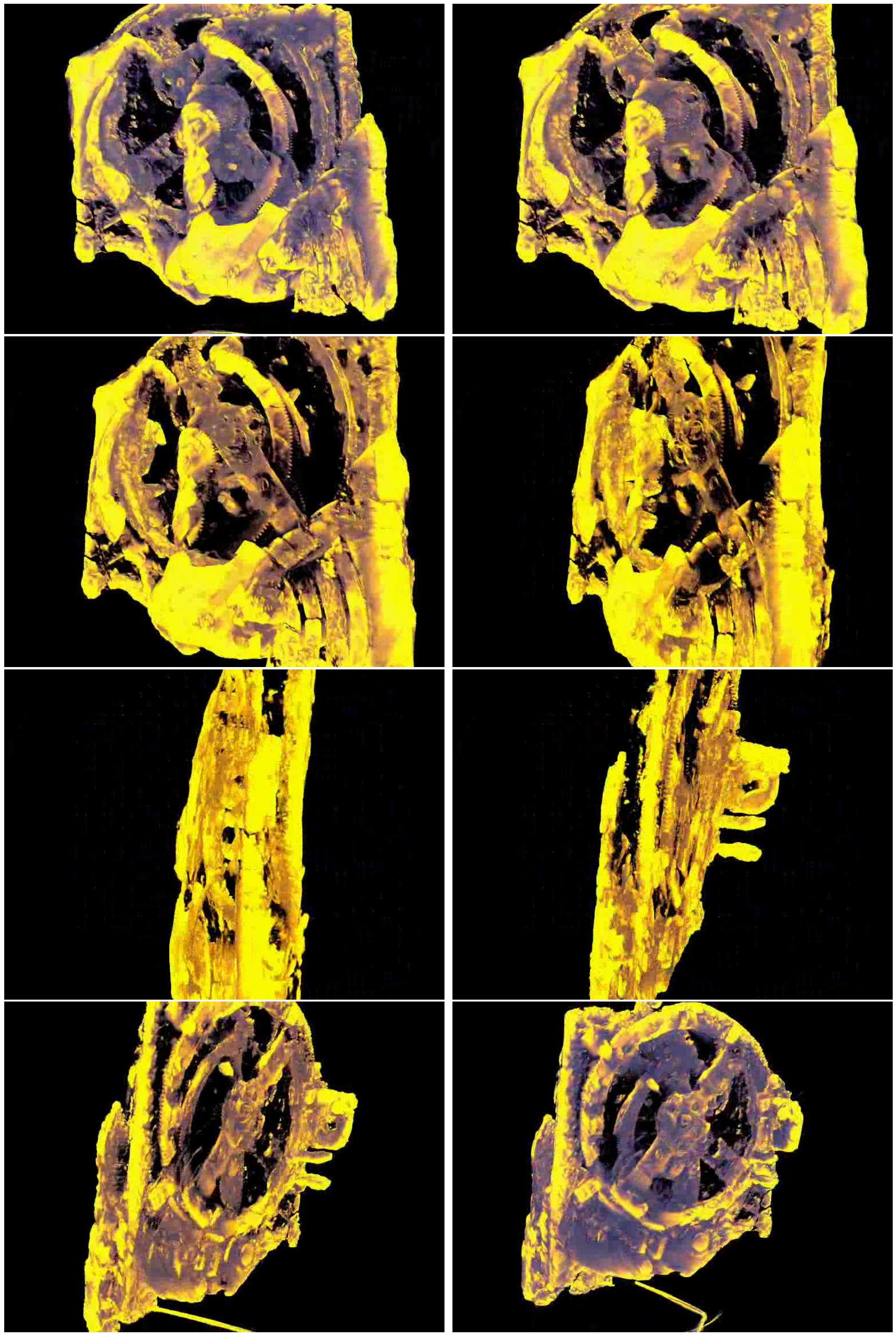


Figure A.7: Series of panels displaying an X-ray observation of a rotating Fragment A. The series starts with a front view of Fragment A, and follows one revolution around the artifact. The images are attained from a movie provided by the AMRP, in which they expand on their research.



A.3 Slicing Fragment A

X-ray micro-focus computed tomography (CT) imaging

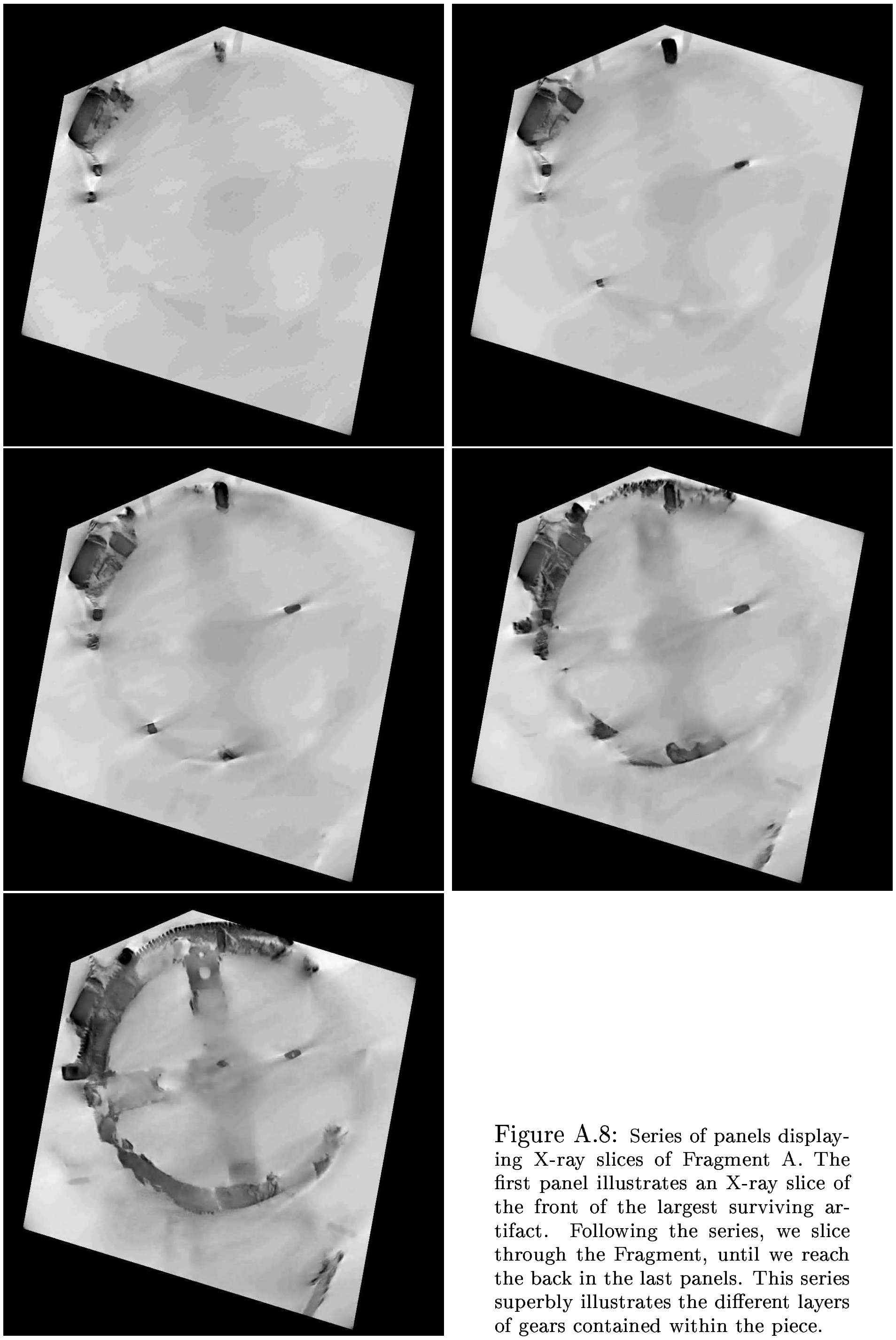
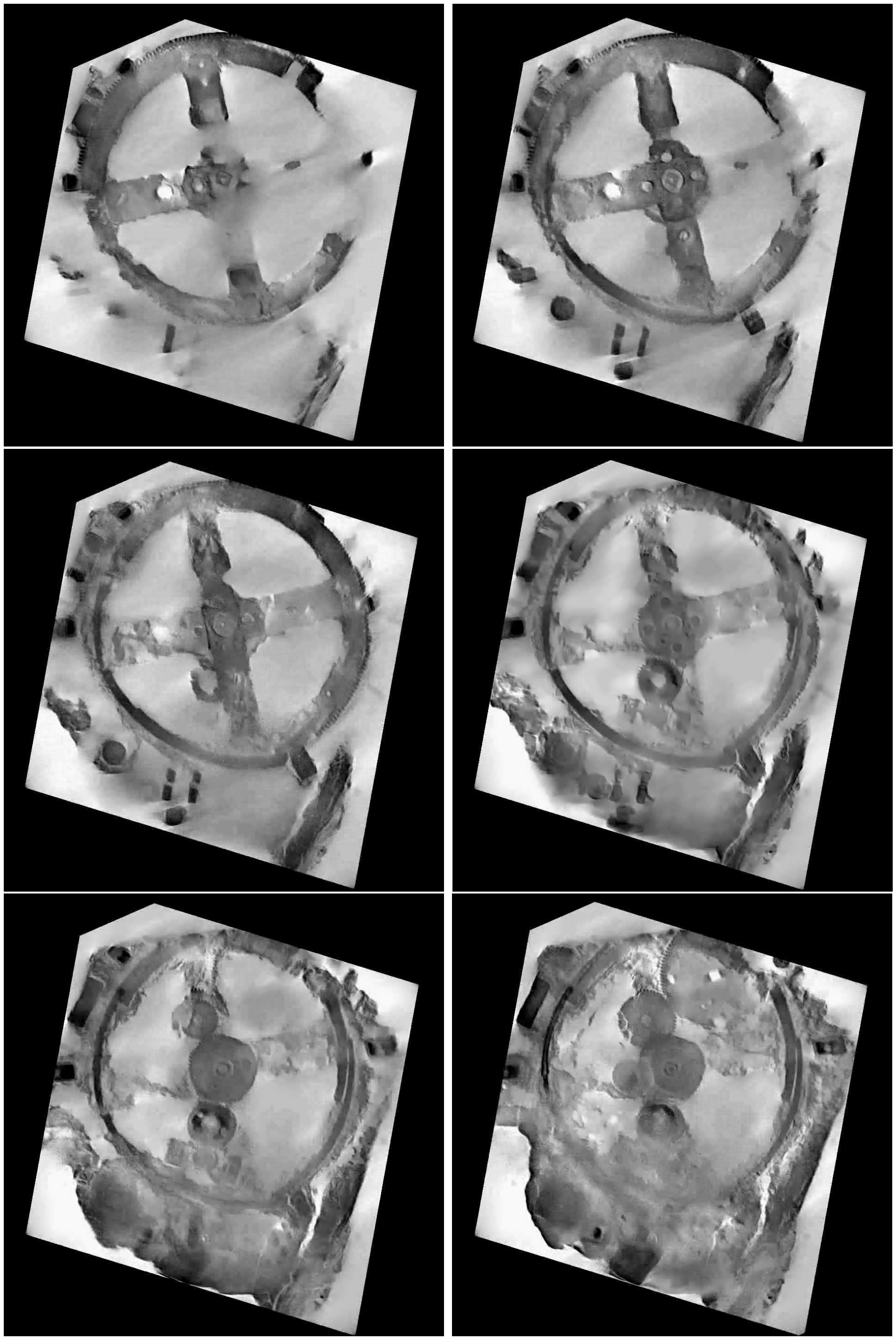
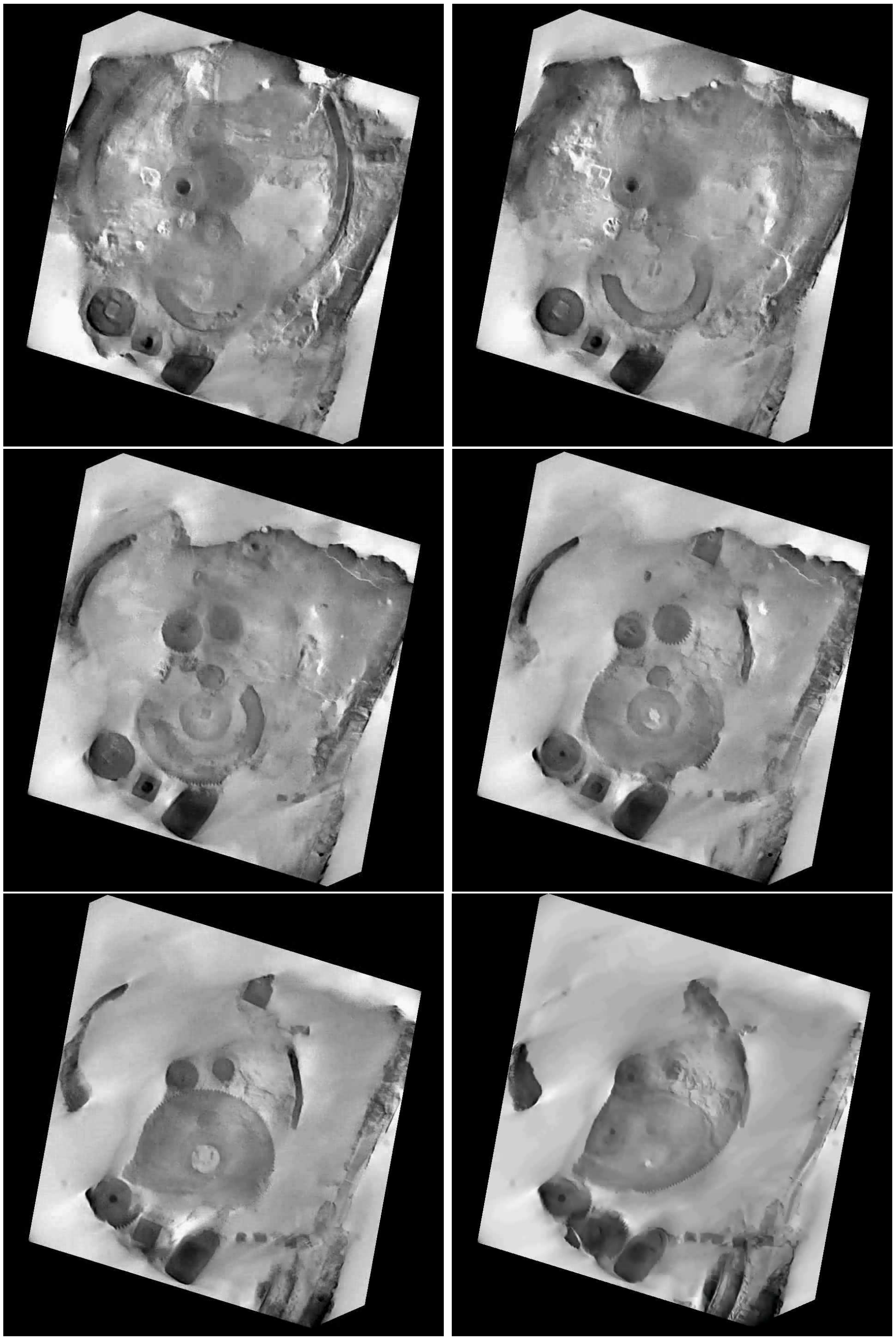
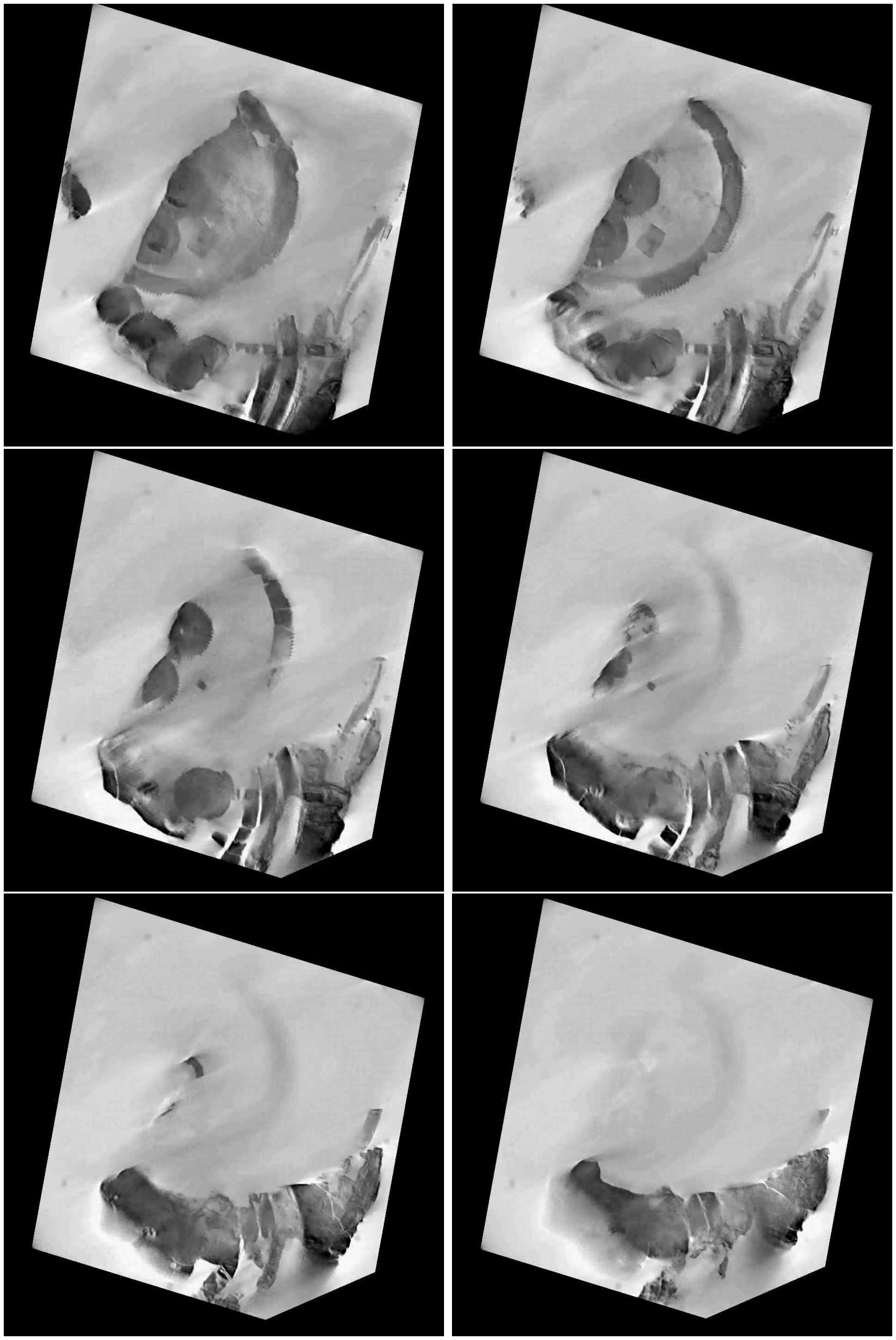


Figure A.8: Series of panels displaying X-ray slices of Fragment A. The first panel illustrates an X-ray slice of the front of the largest surviving artifact. Following the series, we slice through the Fragment, until we reach the back in the last panels. This series superbly illustrates the different layers of gears contained within the piece.







A.4 Alternative view of gearing scheme

This section shows an alternative view on the schematic gearing of the reconstruction of the Antikythera Mechanism, as proposed by Freeth et al. (2006). The series starts with the large Sun Wheel, in red, which propels the gear train for the Metonic cycle. In the second panel the gear train for the Callippic cycle has entered, and the gear train for the Moon pointer is beginning to form. Through panels two till six, this gear train is introduced. In panels six till eight, the remaining gear trains for the Saros cycle and the Exeligmos are formed.

In the final three images, the gearing diagram slightly rotates. Thus providing with an alternative survey of the schematic.

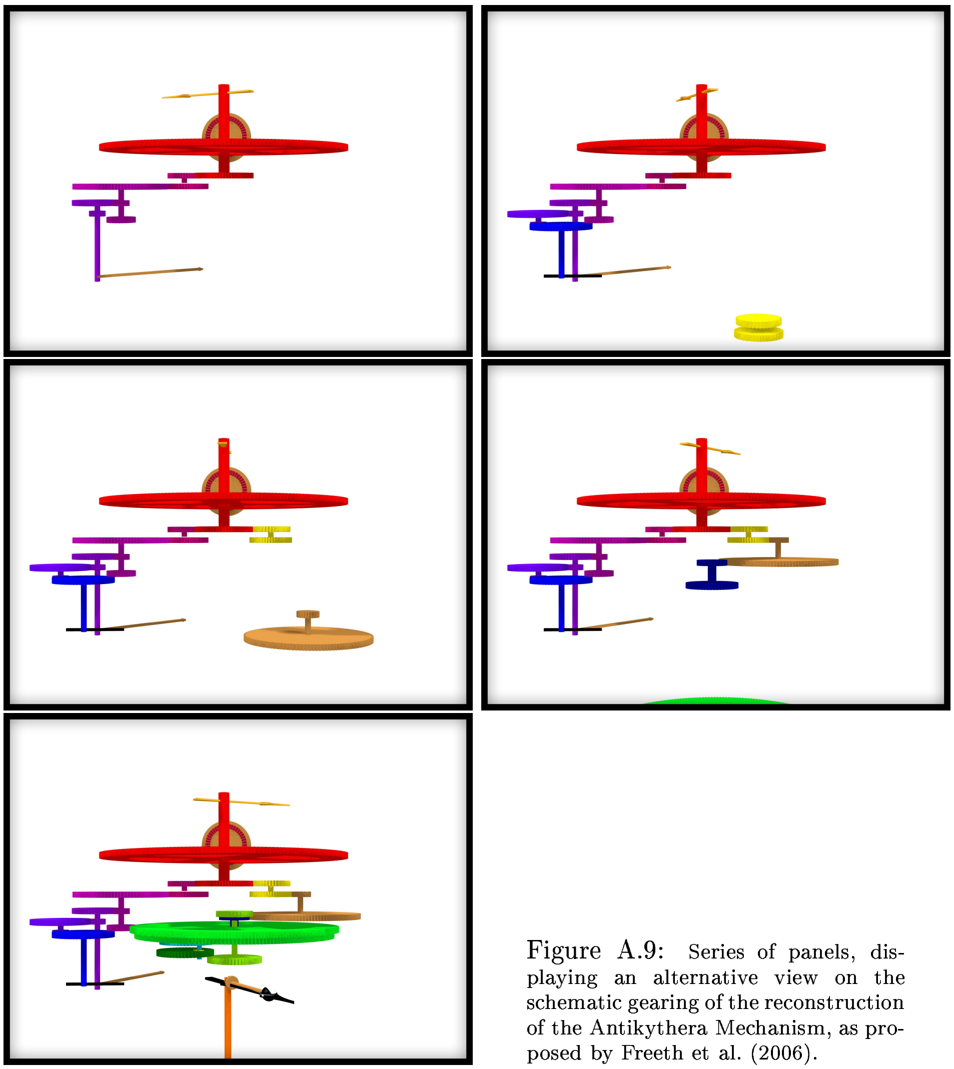
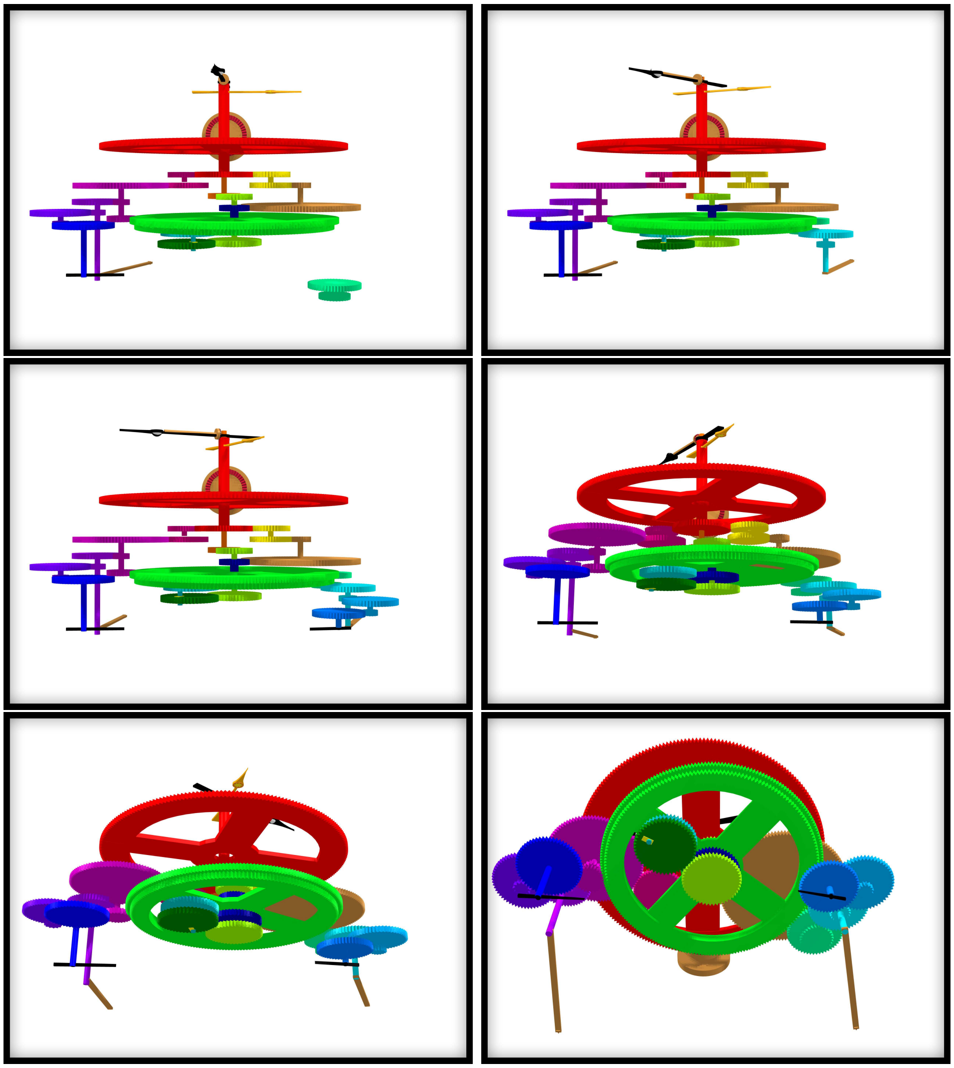


Figure A.9: Series of panels, displaying an alternative view on the schematic gearing of the reconstruction of the Antikythera Mechanism, as proposed by Freeth et al. (2006).



Acknowledgements

I would like to thank the AMRP for providing access to the movies displaying the X-ray observations of the Fragments of the Antikythera Mechanism. The X-ray data were gathered by a team from X-Tek Systems (UK)/Metris (NL).

Thanks to Carel Hofland, from *het Museum van het Nederlandse Uurwerk* in Zaandam (NL), for providing us with the necessary literature.

I would like to thank Jan Willem Pel, for his benevolence to exchange ideas about the subject, and his significant contribution to both the research described in this paper, as well as the realization of this thesis.

To conclude, I would like to thank Rien van de Weijgaert for his endless enthusiasm regarding the subject, as well as his availability throughout the entire project. I am grateful for presenting me the possibility to write a master thesis in astronomy, about one of the most extraordinary and mind-boggling astronomical mechanisms of antiquity, known to date.

N.B.

List of Figures

All images were made by the author, except where mentioned.

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