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SAVING THE PHENOMENA: THE BACKGROUND TO PTOLEMY'S PLANETARY THEORY

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The slogan "saving the phenomena" was taken by Pierre Duhem as the central motivation for ancient and medieval mathematical astronomy, largely based on the report in Simplicius (sixth century A.D.) who attributed this expression to Plato (fourth century B.C.). One of Duhem's claims is that Ptolemy's goal was to "save the phenomena", and it is this claim that needs to be analysed. My view is that the success of the *Almagest* has obscured Ptolemy's innovations, and the modern tendency to give credit for Ptolemy's methodology to earlier astronomers is based on various misunderstandings. As a matter of principle, I do not simply take authors as reliable in reporting on their predecessors without strong corroborating testimony from sources contemporary with those predecessors, or other good reasons for accepting what is asserted. I consider this principle valid for all historical periods, though it is particularly apt in dealing with authors in late Antiquity who tell us about their predecessors, some of whom lived a thousand years earlier. In all cases a discussion of the reliability of sources should precede using them for historical purposes.

The first task is to examine the use of the term 'phenomena' in astronomy, and whether there were significant changes in it over time. It is then appropriate to turn to the meaning of 'saving' those phenomena, as this expression was understood up to the time of Ptolemy. In order to do so, it will be useful to revisit the content and the aims of Ptolemy's *Almagest* (composed *c.* 150 A.D.). Finally, we will sketch an alternative to the standard account of astronomy leading up to Ptolemy.

What were the phenomena of astronomy, and were they all subject to mathematical treatment? What kinds of astronomical observations are reported in ancient sources? What is the relationship of these observations to the theories that were then devised?

Let us begin with the *Almagest*, which is surely the most important ancient astronomical text that survives. What Ptolemy does is unprecedented in many ways with respect to earlier extant astronomical works. First, the parameters for his planetary models are derived explicitly by geometric techniques from specific dated observations — this feature is not found in any earlier work. The observations cover more than 800 years, ending with those Ptolemy made himself. Though Babylonian observations are reported, there is no hint in the *Almagest* of any Babylonian scheme for computing planetary positions.[1] Second, Ptolemy reduces his models to tables, and the means by which the tables are constructed are explicitly given — the appeal is to geometry, not to the arithmetic schemes of the Babylonians. It is important to emphasise Ptolemy's methodological innovation of basing his arguments on specific

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dated observations, for this led him to preserve observations of his predecessors that are nowhere else to be found. The alternative claim in Antiquity was that parameters were derived from a large but unspecified set of observations made over a long time — a claim that probably appeared to some as stronger than a claim based on a few, relatively isolated, observations by a small number of observers. By way of contrast, the Babylonian arithmetic schemes were also quite successful in accounting for planetary positions, but the extant Babylonian tablets that preserve the schemes, either as tables or as procedure texts, display no interest in the derivation of these schemes from the observations that are preserved in a separate series of tablets.[2] While it is now clear that the Greeks (and Romans) had access to both the schemes and the observations of the Babylonians, there is nothing to suggest that they had any idea how they were related to each other.

What are the phenomena dealt with in the *Almagest*? These phenomena are what we generally consider to be the subject of mathematical astronomy, one of many signs of the success of the *Almagest* in defining the subject of astronomy for later generations. For the Sun, Ptolemy considers the length of the seasons and the times of equinoxes and solstices. Then he considers the positions of the Moon and lunar parallax, basing much of his lunar theory on reports of lunar eclipses. There follows a discussion of the apparent sizes of Sun, Moon, and the Earth's shadow at the distance of the Moon during an eclipse, in order to determine the times and magnitudes of eclipses. Later, Ptolemy determines the parameters for his models of Venus and Mercury based on their observed positions, notably at greatest elongations from the mean Sun, and of the outer planets based on their observed positions, notably at oppositions to the mean Sun. He then considers additional planetary phenomena that had been central to the Babylonians: risings and settings, retrograde motion, and stationary points. Ptolemy also has a discussion of the precession of the fixed stars, and includes a catalogue of them as well.

How do these phenomena compare with those discussed in previous Greek works that deal with astronomy? I avoid the expression 'astronomical works' because there does not seem to have been such a genre of Greek literature before Ptolemy, and important discussions appear in a variety of literary contexts. In ancient historical texts there are occasional references to observed eclipses (although it should be noted that many of the reports are problematic in various ways), and at best they give the time of an eclipse together with a remark on totality in the case of a solar eclipse. In no instance outside the *Almagest* is an eclipse report given in the context of a mathematical argument for constructing or testing a model. As for the Sun, there is no unambiguous evidence for an observation of a solstice (rather than a computation that might be based ultimately on Babylonian data); seasonal lengths are reported (notably in the *Ars Eudoxi*, a text of the second century B.C., preserved uniquely on a papyrus now in Paris) but not the dates of the observations. Dated observations of equinoxes that go back as far as 162 B.C. are preserved in the *Almagest*,[3] but there is no evidence outside the *Almagest* that they were used for any theoretical purpose. It is generally assumed that Hipparchus so used them, on the basis of remarks in the *Almagest*, but I do not take that interpretation of the *Almagest* as certain. In the first place, this is not quite what Ptolemy says, and in the second place Ptolemy's derivation of the solar parameters depends on the concept that the position of a celestial body is made up of two components, a mean position and a correction for anomaly — there is no evidence that Hipparchus or anyone else prior to Ptolemy held such a view. In particular, nowhere in the *Almagest* does Ptolemy attribute to Hipparchus a mean solar, lunar, or planetary position. This is not to deny that the concepts of eccentric and epicylic models were considered by Greeks and Romans prior to Ptolemy, for there is evidence in extant texts of these models. Rather, it is to deny that there is any persuasive evidence that Ptolemy's treatment of these models was anticipated by any of his predecessors.

As for the planetary phenomena, there are no dated observations outside the *Almagest* and none in the *Almagest* between the third century B.C. and Ptolemy's immediate predecessors. In particular, there are no dated planetary observations attributed to Hipparchus. In other words, in contrast to the Babylonians who recorded the risings, settings, and stationary points of the planets over at least six centuries, the Greeks did not see any reason to do so or, if some of them did, it was so marginal to their concerns (i.e., the concerns of those elements in society represented by the extant literature) that there is hardly any echo of them.[4]

One of the great surprises in checking ancient literature is that the word in Greek for planetary station first appears in Diodorus of Sicily (first century B.C.). Similarly, the earliest occurrence of a term for retrograde motion appears in Cicero (first century B.C.).[5] After the first occurrences, there are many more in quick succession, i. e., these terms became widespread from the first century B.C. on. In Diodorus's *Bib. hist.* i.81, we read:

> For the positions and arrangements of the stars as well as their motions have always been the subject of careful observations among the Egyptians, if anywhere in the world; they have preserved to this day the records concerning each of these stars over an incredible number of years, the subject of study having been zealously preserved among them from ancient times, and they have also observed with the utmost avidity the motions, the periods (*periodous*), and the stations (*sterigmous*) of the planets, as well as the influence of each one on the generation of all living things.... And according to them the Chaldaeans of Babylon, being colonists from Egypt, enjoy the fame which they have for astrology because they learned that science from the priests of Egypt.[6]

Elsewhere Diodorus (ii.31) refers to Chaldean observations taken over a span of some 473,000 years which, as he says, is truly incredible![7] It is quite amazing that stations and retrograde motion which we take to be the fundamental characteristics of planetary motion are not mentioned explicitly in any earlier Greek text. It has long been assumed that in the *Metaphysics* Aristotle presents the spheres of Eudoxus in order to account for retrograde motion, but he does not say so — this comes from Simplicius's commentary to Aristotle's *De caelo*. In addition, it is assumed that since the phenomenon of retrograde motion is so 'obvious', surely the Greeks must have noticed it. But this is not a good historical argument, for the question is whether they took the phenomenon to be worthy of notice, and whether it was to be explained by a sophisticated model. If we look at Aristotle's *De caelo*, *Meteorology*, and *Posterior analytics*, we find descriptions of a great many celestial phenomena, but not retrograde motion. Essential to the claim that Eudoxus's model is to account for planetary retrograde motion is that Spheres 3 and 4 rotate in opposite directions. But this feature of the model is not mentioned by Aristotle, and again it is Simplicius who supplies the information. At the time of Simplicius, retrograde motion was a commonplace in astronomical discussions, but I see no reason to accept his claim that it was equally central at the time of Aristotle. In other words, the ingenuity of Schiaparelli in deciphering the text of Simplicius in the nineteenth century should not lead us to believe that Simplicius is a reliable witness to the state of astronomy some 900 years earlier.[8] It seems to me that in many cases Simplicius has elaborated on material he found in Proclus (fifth century A.D.) and others, but this deserves separate treatment.

What about Apollonius's theorem on stationary points? Doesn't this prove that the phenomenon of retrograde motion was known by him? Apollonius flourished about 200 B.C.; his extant works concern mathematics rather than astronomy, and his theorem on stationary points is first reported in the *Almagest*. I see several difficulties with the claim that Apollonius dealt with this problem in the way Ptolemy suggests. First, it would be odd for Apollonius to find the solution to a problem that no one seems to have raised prior to him, and that was not mentioned even in the century following him. Second, this theorem is not cited by anyone before Ptolemy, and so the issue would seem to have been marginal at best. But a careful reading of the text of the *Almagest* (xii.1) raises further questions about the role of Apollonius, for Ptolemy mentions "other mathematicians and Apollonius" — what was the role of these "other mathematicians" and what was in the (unnamed) source upon which Ptolemy depended? There are very few astronomers whose names appear in the *Almagest*, and most of them are mentioned in the context of an observation they made. For example, Ptolemy does not mention Eudoxus in the *Almagest*, though he is cited in another work by Ptolemy, the *Phaseis*. Menelaus is mentioned in the *Almagest* as an observer, but not for the theorem associated with his name. The two exceptions in the *Almagest* are Hipparchus (whose theoretical work is often criticized by Ptolemy), and Apollonius. It is unclear why Apollonius is given such prominence by Ptolemy.

Are there astronomical phenomena mentioned in ancient texts that are not discussed in the *Almagest*? Indeed, there are phenomena not mentioned in the *Almagest* that Ptolemy discusses in other works: the *Optics*, the *Planetary hypotheses*, and the *Tetrabiblos*. For example, there is much said about optical illusions in the *Optics*, and some of them refer to astronomy. In the *Almagest*, there are only two passages that seem to fall into this category, and it is fair to say that optical illusions are not a main subject of the *Almagest*. The first passage has been understood to refer to what is called the 'Moon illusion', that is, that the Moon appears larger when seen near the horizon than when high in the sky. All Ptolemy says is that:

> If one assumes any motion whatever, except spherical, for the heavenly bodies, it necessarily follows that their distances, measured from the Earth upwards, must vary, wherever and however one supposes the Earth itself to be situated. Hence the sizes and mutual distances of the stars must appear to vary for the same observers during the course of each revolution, since at one time they must be at a greater distance, at another at a lesser. Yet we see that no such variation occurs. For the apparent increase in the sizes at the horizons is caused not by a decrease in their distances, but by the exhalations of moisture surrounding the Earth being interposed between the place from which we observe and the heavenly bodies, just as objects placed in water appear bigger than they are, and the lower they sink, the bigger they appear.[9]

In the *Optics*, Ptolemy explains this phenomenon as purely psychological, and the literature on this illusion is vast and ongoing. But for present purposes, it is more important to note that Ptolemy does not think variation in distance or size is seen on a daily basis, and he is silent on whether there are variations in distance and size over a longer period of time for any celestial body other than the Moon. Yet in the *Planetary hypotheses* Ptolemy is committed to a nesting hypothesis that allows him to vary the planetary distances, based on the planetary models in the *Almagest* without any additional observational data. Moreover, in that work he lists undated measured apparent planetary sizes (not in the *Almagest*) that he takes to refer to the mean distance of the planet, still without discussing variation in apparent size except for the Moon.[10]

The second passage that may deal with an optical illusion occurs in *Almagest* ix.2:

> In general, observations [of planets] with respect to one of the fixed stars, when taken over a great [angular] distance, involve difficult computations and an element of guesswork ... because [among other reasons] the same interval [between star and planet] appears to the observer as greater near the horizon, and less near mid-heaven; hence, obviously, the interval in question can be measured as at one time greater, at another less, than it is in reality.[11]

Toomer took this passage to refer to atmospheric refraction, but in 1545 Gemma Frisius understood it to be about an optical illusion that is overcome by the careful use of instruments.[12] These two passages, taken together, suggest to me that Ptolemy was aware of such problems, but chose to postpone discussion of them to another work. We may note that Kepler's work on optics, the *Paralipomena* (1604), also had the title, "The optical part of astronomy", i.e., in Kepler's view, it is important for an astronomer to understand the principles of optics in order to assess the reliability of observations. I suspect that Ptolemy shared Kepler's view but, since the beginning of Ptolemy's *Optics* is not preserved, it is unclear whether he said so explicitly.

Another topic missing from the *Almagest* is the colours of the planets, although colour plays an important part in Ptolemy's theory of vision, as it did for Aristotle.[13] In Plato's *Republic*, Book X, colours are associated with the planets, and this theme is taken up by Pliny (first century A.D.) who claims that the colours of planets depend on their distances from the Earth.[14] Moreover, Diodorus says that the Chaldeans use, among other things, the colours of planets as signs of coming events.[15] Indeed, Ptolemy associates colours with planets in the *Tetrabiblos* (ii.9), but not in the *Almagest*. In this context it is rather curious that Ptolemy mentions colours of some fixed stars in the *Almagest*, and these designations have been puzzling to many modern readers.[16] But in the *Tetrabiblos* ii.13, Ptolemy tells us: "As for the fixed stars which are close together in some number, we must observe their colours and magnitudes."[17] There are other peculiarities of the star catalogue — each fixed star is assigned a magnitude on a scale from 1 to 6 that is somehow a measure of its apparent brightness,[18] but for Ptolemy it was surely a measure of its apparent size, as is clear in the *Planetary hypotheses*. There is no evidence for this scale prior to Ptolemy, and it seems to be one of his innovations;[19] Ptolemy does not offer a similar scale for the planetary sizes. Rather than entering into the controversy on Ptolemy's possible indebtedness to Hipparchus for the star catalogue that has engendered a considerable recent literature,[20] let me note a third peculiarity of the star catalogue, namely, it is arranged for the epoch A.D. 137 used nowhere else by Ptolemy (the epoch for the tables in the *Almagest* is the beginning of the reign of the Babylonian king, Nabonassar, in 747 B.C.). For these reasons, I suggest somewhat tentatively that the star catalogue was an earlier work by Ptolemy, incorporated by him into the *Almagest* because of its relationship to the discussion of precession.

Another phenomenon that Ptolemy fails to discuss is the "man in the Moon", although it is already mentioned by Aristotle to indicate that we always see the same side of the Moon,[21] and it is a main topic of Plutarch's *On the faces of the Moon*.[22] In the Middle Ages, this phenomenon was used to argue for a distinction between the epicyclic model for the Moon and the eccentric model, for the epicyclic model seems to be incompatible with this phenomenon.[23]

Yet another topic that one might have expected in the *Almagest* is the phases of the Moon in the course of a month: this is discussed by Vitruvius (first century B.C.),[24] and by Plutarch (early second century A.D.),[25] among others.

In sum, it is not so easy to distinguish physical from mathematical phenomena, and Ptolemy's reasons for discussing some matters but not others in the *Almagest* are far from clear. It is much easier to decide in retrospect, that is, with the *Almagest* in hand, what belongs to astronomy and what does not. In my view, the authors in late Antiquity who came after Ptolemy, including Proclus and Simplicius, took what Ptolemy had done as completely natural without appreciating his reasoning. Following them, Duhem found it rather straightforward to make the distinction between mathematical astronomy and physical astronomy. As Duhem put it:

> On the one side there was astronomy — geometers like Eudoxus and Calippus formed mathematical theories by means of which the celestial motions could be described and predicted, while observers estimated to what degree the predictions resulting from calculation conformed to the natural phenomena. On the other side there was physics proper, or to speak in modern terms, celestial cosmology — thinkers like Plato and Aristotle meditated on the nature of the stars and the cause of their movements.[26]

Duhem contrasts the "method of the astronomer" and the "method of the physicist"; subsequently, these methods have been called "instrumentalist" and "realist", although Duhem does not use these terms. Duhem remarks that the method of the astronomer requires that "when its geometric constructions have assigned each planet a path which conforms to its visible path, astronomy has attained its goal, because *its hypotheses have then saved the phenomena*".[27] For Duhem, Ptolemy belongs in the category of those who follow the method of the astronomer.[28]

But what about the expression, "saving the phenomena"? Simplicius is not the first to use it, although he is the earliest source to ascribe this project to Plato. If we restrict this expression to its application in astronomy (which may not be the original context), and expect it to have something to do with mathematical models, then its history to the time of Ptolemy is quite manageable. The expression occurs in one text prior to the *Almagest*, and then in the *Almagest* itself. Moreover, a passage in Geminus will help to illuminate its meaning.[29]

In Plutarch's *On the faces of the Moon* 923A, we are told:

> Thereupon Lucius laughed and said: "Oh, sir, just don't bring suit against us for impiety as Cleanthes thought that the Greeks ought to lay an action against Aristarchus the Samian on the ground that he was disturbing the hearth of the universe because he sought to save the phenomena by assuming that the Heaven is at rest while the Earth is revolving along the ecliptic and at the same time rotating about its own axis."[30]

Plutarch uses "saving the phenomena" to mean accounting for the apparent risings and settings of the stars by assuming the daily rotation of the Earth instead of the daily rotation of the heavens, and the changes in the seasons by assuming that the Earth revolves about the Sun annually rather than the Sun about the Earth. There is nothing about the planets or about mathematical models.

The passage in Geminus (first century A.D.) is more suggestive of the usual sense given to the expression "saving the phenomena":

> It is posited for astronomy as a whole that the Sun, Moon, and five planets move at a constant speed, in a circle, and in a direction opposite to (the daily rotation of) the cosmos. For, the Pythagoreans, who first came to investigations of this sort, posited that the motions of the Sun, Moon, and five planets were circular and smooth. Regarding things that are divine and eternal they did not admit disorder of the sort that sometimes (these things) move more quickly,

> sometimes more slowly, and sometimes they stand still (which they call stations in the case of the five planets). One would not even admit this sort of unsmoothness of motion regarding a man who is ordered and fixed in his movements. For, the needs of life are often causes of slowness and speed for men; but, as for the imperishable nature of the celestial bodies, it is impossible that any cause of speed and slowness be introduced. For which reason they have proposed (the question) thus: How can one explain the phenomena by means of circular, smooth motions?[31]

Here we have the task of the astronomer described as explaining the planetary phenomena by means of circular, smooth motions. The critical consideration for Geminus is that underlying the disorderly state of things as seen in the heavens there must be circular smooth motions because that is required by the nature of the planets as divine and eternal living beings. In other words, for Geminus the goal of the astronomer is to save the phenomena in the sense that he is to seek an underlying orderly reality that can explain the disorderly appearances that are a kind of illusion.[32] It is instructive to compare what Geminus said with the passage in Simplicius's commentary to Aristotle's *De caelo*:

> Plato, in imposing the requirement on the motions of the celestial bodies to be circular, smooth, and ordered, set this problem for the mathematicians: what are the hypotheses that, by smooth, circular, and ordered motions, can save the planetary phenomena?[33]

Geminus invokes the Pythagoreans whereas Simplicius invokes Plato. I think one can understand why Simplicius, as a Platonist, might make this substitution even in the absence of an ancient source to support his claim.

Ptolemy uses the expression, "saving the phenomena", in *Almagest* xiii.2:

> One should try, as far as possible, to fit the simpler hypotheses to the heavenly motions, but if this does not succeed, [one should apply such hypotheses] which do fit. For provided that each of the phenomena is duly saved by the hypotheses, why should anyone think it strange that such complications can characterise the motions of the heavens when their nature is such as to afford no hindrance, but of a kind to yield and give way to the natural motions of each part, even if [the motions] are opposed to one another?[34]

For Ptolemy, it seems that the mathematical agreement of the models (here called "hypotheses") with the observational data is evidence for the physical reality of the models, even if they seem unduly complicated. In particular, he does not accept the constraints of uniform circular motion as the underlying reality, for simplicity is not the ultimate arbiter of the models. Ptolemy appealed to periodic mean motion instead of uniform motion, and periodic mean motion is a much more abstract concept, for it does not require that a celestial body be located at its mean position.[35] According to Ptolemy the phenomena are 'real' and not illusions, for they are the criteria by which the models are judged, not the other way around.

Finally, let me present a brief sketch of an alternative story for the background to Ptolemy's astronomical innovations in planetary theory. Prior to the first century B.C. a trickle of Babylonian astronomical lore reached the Greeks concerning such matters as the length of daylight, calendrical matters, and possibly reports of lunar eclipses, but there is no evidence for the transmission of planetary theory or of horoscopic astrology. The main body of Babylonian celestial science (anachronistically separated into astronomy and astrology) seems to have entered the Greek world in the first century B.C., as attested by horoscopes preserved in papyri, and literary works by Diodorus, Strabo, and Cicero, among others. Moreover, Egypt was probably the place where the transmission took place, judging by similar material from the first century B.C. in Demotic Egyptian.[36] The strongest evidence for an earlier transmission of Babylonian celestial science relied on references to Berosus, but now it is clear that there were two persons with that name, one the historian of Babylon who lived in the early third century B.C., and the other the astrologer who lived in the first century B.C. So references to Berosus the astrologer again point to a transmission of Babylonian lore in the first century B.C.[37] This is how Vitruvius put it:

> For the rest, as to astrology, [i.e.] the effects produced on the human course of life by the twelve signs, the five planets, the Sun, and the Moon, we must give way to the calculations of the Chaldeans because the casting of nativities is special to them so that they can explain the past and the future from astronomical calculations. Those who have sprung from the Chaldean nation have handed on their discoveries about matters in which they have shown themselves to be of great skill and subtlety. And first, Berosus settled in the island of Cos as a citizen and opened a school there.[38]

Babylonian celestial science clearly made a deep impression on the Greeks and Romans, and forecasts of life events by means of horoscopic astrology appealed to significant numbers of them. But there was also opposition to this form of divination on the grounds that it was irrational. For example, Cicero remarks:

> Again, when the Chaldeans say, as they are bound to do, that all persons born anywhere in the habitable earth under the same horoscope, are alike and must have the same fate, is it not evident that these would-be interpreters of the sky are of a class who are utterly ignorant of the nature of the sky?[39]

The success of Babylonian astronomy in calculating planetary phenomena was puzzling, for there was nothing that could be justified philosophically in what was done — after all, the 'Chaldeans' were just using arithmetic schemes. By the time of Geminus in the first century A.D., the question for philosophically minded Greeks had become, "How can we account for the Babylonian schemes by proper (i.e., Greek) geometric methods that are philosophically sound?" Geminus made a good effort to do so, but the project as he conceived it was doomed to failure because there is no simple way to construct geometric models that can account for the

Babylonian arithmetic schemes.[40] On the other hand, one could use the geometric models, such as the eccentric model, to account for changes in the daily progress of a celestial body qualitatively while using Babylonian schemes for quantitative purposes. That, at least, would lend plausibility to the schemes.[41] It is also clear that for Geminus retrograde motion is a prominent feature of planetary motion that needs to be accounted for, and this is consistent with my claim that Greek interest in retrogradation depended on the arrival of the Babylonian planetary schemes where this phenomenon is well represented.

In the second century A.D. Ptolemy completely transformed the question. Instead of seeking to account for the Babylonian schemes, he sought to account for the planetary phenomena directly by means of geometric models. For this reason, he had no use for the schemes of the Babylonians, but their observations could still be used for his own purposes. By constructing tables, Ptolemy could beat the so-called Chaldeans at their own game — for it was their skill at calculations that was so admired. Moreover, observations (both Babylonian and Greek) that had been marginal — they had served little purpose for the Greeks, and had little epistemic status compared to knowledge that supposedly derived from great antiquity — now took on a central role in the geometric arguments that lie at the heart of the *Almagest*. Ptolemy's appeal to periodic mean motions, rather than to uniform motions, meant that he understood the nature of the gods to be different from what Geminus and others believed, but Ptolemy challenged neither the divine status of the planets nor their eternal unchanging nature.

For reasons that may well have to do with his sense of audience and its preference for the old over the new, Ptolemy did not stress his innovations. As a result, these innovations have been taken by most ancient and modern scholars as commonplace among his predecessors, almost entirely based on the evidence of the *Almagest* itself. This was the price that Ptolemy may have been prepared to pay for success and, indeed, the *Almagest* became the standard astronomical work for over 1400 years in a variety of cultural settings around the Mediterranean and beyond.

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REFERENCES

1. *Cf.* A. Jones, "Hipparchus's computations of solar longitudes", *Journal for the history of astronomy*, xxii (1991), 101–25 (espec. p. 122). The earliest dated observation in Greco-Latin scientific literature reported in the name of a specific individual is found in Pliny's *Hist. nat.* ii.180 (*Pline l'Ancien, Histoire naturelle* (37 vols [editors and translators vary], Paris, 1947–1985), ii [ed. and transl. by J. Beaujeu], 79), but this observation of a solar eclipse was not used to derive the parameters of a model. Earlier, in Aristotle's *Meteorology*, it is remarked that "we

ourselves have observed Jupiter coinciding with one of the stars of the Twins and hiding it ..." (343b30), but no date is given, and no attempt is made to use this observation to construct a model. For Ptolemy's use of observations in his lunar theory, including those of Hipparchus, see B. R. Goldstein and A. C. Bowen, "The role of observations in Ptolemy's lunar theories", in *Ancient astronomy and celestial divination*, ed. by N. M. Swerdlow (forthcoming).

2. A text Britton calls Text S is "the only [Babylonian] text known to combine observational material ... with theoretical functions from mathematical lunar theory": J. P. Britton, "An early function for eclipse magnitudes in Babylonian astronomy", *Centaurus*, xxxii (1989), 1–32 (espec. p. 1). But there are no direct comparisons between theory and observations even in that text, and certainly nothing on the derivation of the mathematical functions from the observations.
3. *Almagest* iii.1 (transl. by G. J. Toomer, *Ptolemy's Almagest* (New York and Berlin, 1984), 133 and 133 n8). It is often assumed that the three equinoxes of 162 to 158 B.C. were observed by Hipparchus, but Toomer reports his view that they were not made by Hipparchus himself, "but were simply adduced by him for comparison".
4. A passage in *Almagest* ix.2 (Toomer, *op. cit.* (ref. 3), 420) may be taken to be such an echo, but I think it more likely to be an allusion to Babylonian records than to Greek: "It is also [confusing] that most of the ancient [planetary] observations have been recorded in a way which is difficult to evaluate, and crude. For the more continuous series of observations concern stations and phases [i.e., first and last visibilities]."
5. Cicero, *De natura deorum*, ii.51, ed. and transl. by H. Rackham (Cambridge, Mass. and London, 1933), 173; Cicero, *De divinatione* ii.89 in *Cicero, De senectute, De amicitia, De divinatione*, ed. and transl. by W. A. Falconer (New York and London, 1923), 471. I am grateful to Alan C. Bowen for searching the data bases, TLG (Thesaurus Linguae Graecae) and PHI (Packard Humanities Institute), for early occurrences of the relevant terms in Greek and Latin.
6. C. Oldfather, *Diodorus of Sicily* (12 vols, Cambridge, Mass. and London, 1933), i, 278–9. Needless to say, Diodorus and other classical authors are no longer to be taken as reliable sources for the content of either Egyptian or Babylonian astronomy in the absence of support from the original documents of those ancient cultures that are now available.
7. Oldfather, *op. cit.* (ref. 6), i, 457; *cf.* Cicero, *De divinatione* i.2; Falconer, *op. cit.* (ref. 5), 223f; Pliny, *Hist. nat.* vii.193; *Pline l'Ancien*, *op. cit.* (ref. 1), vii [ed. and transl. by R. Schilling], 113.
8. For Schiaparelli's account, see T. L. Heath, *Aristarchus of Samos* (Oxford, 1913), 194ff.
9. *Almagest* i.3 (Toomer, *op. cit.* (ref. 3), 39); *cf.* A. M. Smith, *Ptolemy's theory of visual perception*, *Transactions of the American Philosophical Society*, lxxxvi/2 (Philadelphia, 1996), 2, 151.
10. See B. R. Goldstein, *The Arabic version of Ptolemy's* Planetary hypotheses, *Transactions of the American Philosophical Society*, lvii/4 (Philadelphia, 1967).
11. Toomer, *op. cit.* (ref. 3), 421.
12. *Cf.* B. R. Goldstein, "Remarks on Gemma Frisius's *De radio astronomico et geometrico*", in *From ancient omens to statistical mechanics: Essays on the exact sciences presented to Asger Aaboe*, ed. by J. L. Berggren and B. R. Goldstein (Copenhagen, 1987), 167–79.
13. See Smith, *op. cit.* (ref. 9), 27.
14. Pliny, *Hist. nat.* ii.79; Beaujeu (ed.), *op. cit.* (ref. 1), 34.
15. Diodorus, *Bib. hist.* ii.30; Oldfather, *op. cit.* (ref. 6), i, 451; *cf.* H. Hunger and D. Pingree, *MUL.APIN: An astronomical compendium in cuneiform* (Horn [Austria], 1989), 149f.
16. *Cf.* R. C. Ceragioli, "Solving the puzzle of 'red' Sirius", *Journal for the history of astronomy*, xxvii (1996), 93–128 (espec. pp. 95 and 122 n12).
17. F. E. Robbins, *Ptolemy: Tetrabiblos* (Cambridge, Mass. and London, 1964), 217.
18. See J. Herschel, *Outlines of astronomy* (London, 1849), 491ff.
19. *Cf.* J. Evans, "On the origin of the Ptolemaic star catalogue", *Journal for the history of astronomy*, xxviii (1987), 155–72, 233–78 (espec. pp. 260ff).
20. For a critical summary of this literature, see N. M. Swerdlow, "The enigma of Ptolemy's catalogue

of stars", *Journal for the history of astronomy*, xxiii (1992), 173–83.

21. Aristotle, *De caelo* ii.8; Aristotle, *On the heavens*, ed. and transl. by W. Guthrie (Cambridge, Mass. and London, 1960), 189.
22. Plutarch, *Moralia: Concerning the face that appears in the orb of the Moon*, ed. and transl. by H. Cherniss (Cambridge, Mass. and London, 1957), 41ff.
23. This view was taken by Roger Bacon, Buridan, and Levi ben Gerson, among others: see, e.g., A. Gabbey, "The case of the rotating Moon", in *Revolution and continuity*, ed. by P. Barker and R. Ariew (Washington, D.C., 1991), 95–129 (espec. pp. 115f).
24. Vitruvius, *De arch.* ix.2; Vitruvius, *On architecture*, ed. and transl. by F. Granger (2 vols, Cambridge, Mass. and London, 1956), ii, 227ff.
25. Cherniss (ed.), *op. cit.* (ref. 22), 103.
26. P. Duhem, *To save the phenomena: An essay on the idea of physical theory from Plato to Galileo*, transl. by E. Doland and C. Maschler (Chicago, 1969), 114.
27. Duhem, *op. cit.* (ref. 26), 6; emphasis in the original. Note that the "path" of a planet is a concept developed by Kepler rather than by Ptolemy (*cf.* P. Barker and B. R. Goldstein, "Distance and velocity in Kepler's astronomy", *Annals of science*, li (1994), 59–73). The English version of Duhem may be misleading here, for the original French (Paris, 1908, p. 3) has *marche* that can mean 'progress' as well as 'path'.
28. Duhem, *op. cit.* (ref. 26), 16ff.
29. Duhem missed the passage in Plutarch, but he was aware of the use of this expression by Theon of Smyrna (date uncertain; most probably after Ptolemy, in the third or fourth century A.D.), and Proclus, as well as by Simplicius.
30. Cherniss (ed.), *op. cit.* (ref. 22), 55.
31. Geminus, *Intro. ast.* 1.19–22; *Géminos, Introduction aux phénomènes*, ed. and transl. by G. Aujac (Paris, 1975), 5; A. C. Bowen and B. R. Goldstein, "Geminus and the concept of mean motion in Greco-Latin astronomy", *Archive for history of exact sciences*, l (1996), 157–85 (espec. p. 180).
32. Smith (*op. cit.* (ref. 9), 19) understands the ancient view of "saving the phenomena" (particularly in optics) to mean that the appearances in the sensible world are illusions that have to be rationalized or "saved" by being reduced to perfect regularity.
33. The text of Simplicius appears in: *Autolycos de Pitane, La sphère en mouvement*, ed. and transl. by G. Aujac (Paris 1979), 159.
34. Toomer, *op. cit.* (ref. 3), 600–1.
35. On the distinction between arithmetic mean motion and periodic mean motion, see Bowen and Goldstein, *op. cit.* (ref. 31), 159.
36. *Cf.*, e.g., O. Neugebauer and R. Parker, "Two demotic papyri", *Journal of Egyptian archaeology*, liv (1968), 231–5; F. Rochberg, "Nabu-rimannu", in *Great lives from history: Ancient and medieval series*, ed. by F. N. Magill (Pasadena, 1988), 1439–43; A. Jones, "Evidence for Babylonian arithmetic schemes in Greek astronomy", in *Die Rolle der Astronomie*, ed. by H. D. Galter (Graz, 1993), 77–94.
37. See A. Kuhrt, "Berossus' *Babyloniaka* and Seleucid rule in Babylonia", in *Hellenism in the East*, ed. by A. Kuhrt and S. Sherwin-White (Berkeley and Los Angeles, 1987), 32–56 (espec. pp. 36ff).
38. Vitruvius, *De arch.* ix.6; Granger (ed.), *op. cit.* (ref. 24), ii, 245.
39. Cicero, *De divinatione* ii.92; Falconer (ed.), *op. cit.* (ref. 5), 475.
40. *Cf.* Bowen and Goldstein, *op. cit.* (ref. 31).
41. *Cf.* Jones, *op. cit.* (ref. 1), and Jones, *op. cit.* (ref. 36), espec. p. 89.