CHAPTER 1

PRECISION OF TIME OBSERVATION IN GRECO-ROMAN ASTROLOGY AND ASTRONOMY

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Abstract

This article reviews the evidence for the precision of observed (or allegedly observed) time determinations in the Greek astral sciences. In the practice of astrology, the determination of times—most commonly times of births—was the province of lay observers, and the precision was not normally more refined than to the seasonal hour. In astronomy, the extant observational records show a broad trend towards more refined precision, though the apparent culmination of this trend in Ptolemy is due not only to his employment of the armillary astrolabe as a precision time-telling instrument but also to his penchant for fabrication and tampering in his observation reports. Ptolemy's claims to have attained to unprecedented time precision in the observations on which his tables were ostensibly based likely contributed to their early and widespread adoption by astrologers.

Introduction

The practice of astrology was one of the most conspicuous points of contact between technical astronomy and the lay public in antiquity. The personal horoscope is the emblematic document of this contact. A client, who could be a person of practically any social status and who would likely be ignorant of all but the most obvious facts of astronomy, provided the astrologer with his or her date, time, and (if not local) place of birth, and the astrologer employed astronomical tables or almanacs to determine the celestial longitudes of the Sun, Moon and planets and the points of the ecliptic that were crossing the horizon and meridian planes at that time and place. This information, which is usually all that was written down in the horoscope document that the client took away, provided the basis for the astrological interpretations and forecasts that the astrologer expounded orally to the client.

The sceptic philosopher Sextus Empiricus (c. 200 CE), in his attack on the astrologers' claims to knowledge, frames part of his argument on a paradigmatic model of horoscopic practice that, he claims, came from the astrologers themselves, according to whom this was how a horoscope was originally determined (*Adversus Mathematicos* 5.28):

> By night, they say, the Chaldean sat atop some high hilltop, and another person attended to the woman in labor until she gave birth, and the moment that she had given birth he gave a signal with a gong to the one on the hilltop. And when he heard it, he took note of the zodiacal sign that was rising as the ascendant. By day, however, he resorted to time-keeping devices (ὡροσκόπια) and the motions of the Sun.

Sextus thus describes two strategies, depending on whether the birth happens during the nighttime or the daytime. The nighttime case is the simplest: no time measurement is required, since through the signal the crucial astronomical datum that changes most rapidly, the ascendant point of the ecliptic, is directly observed simultaneously with the birth. But it is exceedingly doubtful whether any ancient horoscope was established in this manner; this is really a kind of idealized thought experiment that allows Sextus to zero in on the questions of whether a simultaneous observation is possible (since sound takes time to travel) and whether giving birth is an instantaneous event. The daytime case brings us closer to the reality of astrological practice: the attendant signals with the gong, the Chaldean hears it and measures the time of day using a sundial or water clock, and then, presumably, he consults astronomical tables to calculate the longitude of the ascendant, since the stars are not visible by day.

Measurement of time is actually implicated in two ways in Sextus's daytime strategy. The Chaldean observes the time by means of an instrument at the moment of birth, but the tables that he uses to obtain the ascendant are also derived in part from timed observations. The immediate source for the ascendant would have been a table of oblique ascensions, which is a kind of trigonometrical table incorporating two empirical constants, the obliquity of the ecliptic and the terrestrial latitude. Both constants could be derived from solstitial extrema of the Sun's noon altitude observed without requiring precise time measurements. But to use the ascension table to find the ascendant, one had to know the Sun's longitude, and the empirical foundation of solar tables would be some set of timed observations such as dates and times of solstices and equinoxes.

What is still unreal about Sextus's daytime strategy—unless perhaps we are speaking of the birth of a royal child?—is the assumption that the time of birth is measured or recorded by the astrologer. Under normal circumstances, the astrologer would be informed of the date and time of birth subsequent to the event, perhaps while the person in question was still an infant, but often years and decades later. In other words, it was left to lay people to come up with the individual's birth time.

In this paper, I wish to consider some aspects of the topic of precision in time measurements involved in both the client end of Greco-Roman astrology and in the astronomy on which the practice relied. Although the related topic of accuracy of measurement will come up intermittently, my main concern is how the ancient observers and authors presented their time determinations, which was the principal basis on which an ancient user would have judged the quality of the data. Our primary evidence is, on the one hand, the ancient documentary horoscopes that survive for the most part on papyri from Roman Egypt, and on the other, the astronomical observation reports preserved in Ptolemy's *Almagest* and a few other sources. These are supplemented by other information provided in the astrological and astronomical literature. The evidence is much less abundant than one would wish, so the conclusions offered here are necessarily tentative.

Times in astrological contexts

Time of day or night figures in astrological prognostication already in the Babylonian omen literature. For example, lunar eclipse omen texts preserved from the Old Babylonian period (first half of the second millennium BCE) and the great astral omen corpus *Enūma Anu Enlil* (oldest preserved copies from the seventh century BCE but certainly older in composition) use the division of the night into three "watches" as an element in omen protases (Rochberg-Halton 1988, 20 and 44). When the tradition of eclipse omens was transmitted to Egypt about the middle of the first millennium BCE, the granularity of the time references in the protases remained at the level of partition of night or day into three or four divisions, now expressed as intervals of four or three numbered seasonal hours. So, for example, in the Demotic papyrus *PVind.* D 6278+ (col. IV, 16-18) we find the following scheme associating times of night for lunar eclipses with various nations:[1]

> From the first hour of evening to the third hour of night [belongs to Egypt; from the fourth hour to the sixth] ho[ur belongs to (the) Hebrew; from the] seventh hour to the ninth hour belongs to the [A]morite; [from the tenth hour to the twelfth hour belongs to the country of the Syrian.]

And again, the Greek astrological author Hephaestion of Thebes (c. 400 CE) retails omens such as the following as coming from "the Egyptians of old" (*Apotelesmatica* 1.21):

> If the Sun was eclipsed in Gemini in the first 3-hour interval, they determined that the ruler of Asia was going to die after a year and that the people of first rank were going to be cut down by the mob. If it occurred around the last 3-hour interval, there was going to be destruction and devastation for Italy and Cilicia and Libya and for those who live towards the west. If the Moon was eclipsed in the first 3-hour interval, great harm for the king of Asia and the inhabitants and destruction for quadrupeds, especially flocks...

The more immediate antecedents of Greek horoscopes are the so-called Babylonian horoscopes, of which we have about thirty preserved from the late fifth century through the first century BCE (Rochberg 1998). These documents contain statements of the locations of the Sun, Moon, and planets in the zodiac on the birthdate of an individual as well as astronomical phenomena on dates within the same month or year. The times of the births are specified in various ways, such as "in the first part of the night" or "in the middle watch," which are comparable in precision to the time references in omen protases. Some are expressed to a precision of one half *bēru* (equivalent to one equinoctial hour) or one seasonal hour (*simānu*). However, it is not clear that this more refined precision was reflected in the astronomical data in the horoscopes. The Babylonian horoscopes do not include the ascendant or other cardines, which are especially sensitive to the time of day or night; it is possible that the Moon's longitude, when specified to a precision of degrees, was interpolated between computed or observed daily positions to be correct for the given time.

In Greek horoscopes the times are almost invariably expressed in seasonal hours, and almost always simply by the ordinal number, for example "9th hour of night."[2] (Two horoscopes, preserved in the same

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[1] Restorations and translation by Parker, from Parker 1959, 23.

[2] Major collections of Greek horoscopes are Neugebauer & van Hoesen 1959, Baccani 1992, and Jones 1999a.

manuscript, use ὀψέ, "late," without hour number, apparently signifying sunset.)[3] Smaller units never occur, but one occasionally meets with statements that the time is near or at the beginning or end of the indicated hour, a convention that we will call "nuanced" seasonal hours. We do not know whether there was a conventional interpretation of an unqualified hour number as meaning the beginning, middle, or end of the seasonal hour in question.

It was not only the sceptic philosophers and other critics of astrology who perceived that time precision was a sensitive issue for the validity of a divinatory science that professed to distinguish between the destinies even of twins born a fraction of an hour apart. On occasion astrological authors too deprecated the coarseness with which birth times were provided. Ptolemy, for example, writes as follows (*Tetrabiblos* 3.3):

> … there is often a difficulty concerning the primary and most important (element), namely the fractional part of the hour of birth, because generally speaking only a sighting by people observing scientifically by means of time-keeping "astrolabes" (δι᾽ ἀστρολάβων ὡροσκοπείων, *i.e. sighting instruments capable of functioning as clocks*) right at the time of birth is capable of supplying the minute of the hour, whereas pretty well all the other time-keeping devices that most of those who are more careful employ are capable of deviating from the truth in many ways—sundials on account of distortions incident to the alignments and the gnomons, and water clocks on account of stoppages and nonuniformities in the flow of water through various causes and at random…

It is telling that Ptolemy says that only "those who are more careful" (τῶν ἐπιμελεστέρων) determined birth times by means of sundials or water clocks—let alone more sophisticated astronomical instruments! Sheer guesswork about the time must have been the norm. Two horoscopes on papyrus (out of something like two hundred extant) mention water clocks in connection with the time of birth.[4] But few households would have possessed a sundial or even a simple nonmechanical water clock, and even in a society that gave wide acceptance to the validity and value of astrology, one wonders how many parents experiencing a childbirth would have considered having someone find out the precise time a matter of high priority.

Ptolemy offers a remedy for an inadequately precise given time of birth. One computes the horoscope for the given time, and the longitude at the immediately preceding syzygy of whichever of the Sun and Moon (or both) was above the horizon. Then, one establishes whichever of the Sun, Moon, and planets at the birthdate has the most significant astrological relations (lordship of zodiacal sign, lordship of terms, aspects, etc.) with the degree of the syzygy. If this body is at *n* degrees within its zodiacal sign, the ascendant for the precise moment of birth will have been at *n* degrees within whichever zodiacal sign was found in the provisional calculation using the ascension tables. This was just one of a repertory of astrological algorithms that were devised to refine the longitude of the ascendant, effectively rediscovering the "lost" information about the precise time of birth, through manipulations of the astronomical data pertaining to the date and time as given by the client; others are given by Vettius Valens (e.g. *Anthologiae* 1.4 Pingree = 1.5 Kroll). An obvious fallacy adheres to these methods, since if the corrected ascendant and birthtime are determined strictly from the given crude birthtime, the results will not differentiate between people who were actually born a fraction of an hour apart. Specious claims of prognostic exactitude are entirely in character for Valens; but it is surprising that Ptolemy would let such a thing pass, even if it was sanctioned by tradition.

To cite a typical instance of Vettius Valens's style of high-precision astrology, in *Anthologiae* Book 8 he describes and illustrates a method of forecasting the length of a person's life in years as a function of the ascendant's longitude, using a special numerical table. The tabulated quantities form a sawtooth function, increasing linearly for extended stretches from near zero to a maximum value and then dropping to near zero again. As he points out (8.7 Pingree = 8.6 Kroll), this renders the forecast highly sensitive when the ascendant is close to one of the discontinuities; for example from Cancer 27° to Cancer 28° the predicted upper bound length of life drops from 104 to 6 years. Techniques of the kind described in the preceding paragraph enable Valens to establish a "precise" ascendant, but they depend on accurate knowledge of the Sun's longitude.

In a famous passage (9.12 Pingree = 9.11 Kroll), Valens draws attention to the diversity of astronomical tables in circulation, giving as an illustration the variety of values assumed for the length of

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[3] Horoscopes in *PSI* 1.22 and 1.24, in Neugebauer & van Hoesen 1959, texts 366 and 373.

[4] *PLond.* 1.98, lines 59-61 (text 95 in Neugebauer & van Hoesen 1959) cites a clepsydra for a diurnal birth, while *PHarris* 52 (text 171) states the time as the *n*th kotyla of the night—the numeral is lost—using a fluid measure in place of the usual hour number.

the year, which of course affects the solar longitudes that the tables yield. In common with most astrologers, however, Valens probably had little understanding of the foundations of these tables or the problems of observational precision that made it possible for tables based on conflicting parameters to circulate. Let us now turn now to this topic of precision in timed astronomical observations, beginning with a crucial one of these problems, concerning the determination of times of solstices and equinoxes.

Although the rapidly changing ascendant was the most obvious case of a time-sensitive astrologically significant datum, we have abundant evidence that the practices of Greco-Roman astrology created a demand for precision at the scale of hours in other kinds of predicted astronomical data. Catarchic astrology, which sought to determine auspicious and inauspicious times for various activities, relied heavily on the transient configurations of the Moon with respect to the signs of the zodiac and the other heavenly bodies. A simple example of this kind of forecasting is *POxy.* 65.4483 (c. 200 CE), a letter from one Elis to one Carpus offering the following advice:

> Get together with your friend when the Moon is in Sagittarius. At the fourth hour it is there on Thoth 12; it is there again on the 13th and the 14th, up to the seventh hour.

Again, Pliny the Elder (*Naturalis Historia* 29.9) writes of a fashionable physician named Crinas of Massilia who determined optimal hours, for example for meals, for his patients by consulting an "ephemeris," that is, a table giving daily computed longitudes of the Moon and the other heavenly bodies. Many fragments of ephemerides are extant on papyrus, and a frequent feature is a column giving the times in seasonal hours when the Moon crosses the boundary between one zodiacal sign and the next, sometimes to a precision of a fraction of an hour.[5] We also have planetary almanacs giving the computed dates and times in seasonal hours when each of the five planets crossed the boundaries of zodiacal signs (Jones 1999b, 324-326).

Solar observations: solstices and equinoxes

Book 3 of Ptolemy's *Almagest* is our sole source of timed observation reports of equinoxes. In *Almagest* 3.1 (Toomer 1984, 133-134) Ptolemy cites from Hipparchus's *On the Shifting of the Solstitial and Equinoctial Points* six autumnal equinox reports spanning the interval 162-143 BCE, two variant reports of the same vernal equinox of 146 BCE, and vernal equinox reports from 135 and 128 BCE. He also indicates that, according to Hipparchus, there were vernal equinox reports from the interval 146-141 BCE—not necessarily for every year but including one from 141—that were consistent with the one from 146, in the sense that the intervals between them were consistent with a 365 ^{1}/4 day tropical year, and vernal equinox reports from 134-129 BCE—again not necessarily for every year—that were consistent with the one from 135. These are not only the earliest reports of timed equinox observations in Greek astronomy to be transmitted, but even the earliest that we hear of. The reports are summarized below, with the dates converted into the proleptic Julian calendar, and, for comparison, true UT times of equinox to the nearest quarter hour:[6]

Autumnal equinoxes		
162 September 27	about sunset	Sept 27 00:30
159 September 27	early morning (πρωίας)	Sept 26 18:00
158 September 27	at the 6th hour (of day)	Sept 26 23:45
147 September 26/27	at midnight	Sept 26 15:45
146 September 27	early morning	Sept 26 21:30
143 September 26	at eve (ἑσπέρας)	Sept 26 15:15
Vernal equinoxes		
146 March 24	early morning	March 24 13:15

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[5] Jones 1999b, 319-324. *POxy. astron.* 4176 (Jones 1999a, vol. 2, 174-175), from 111 CE, gives times of lunar sign-entries with fractions of ^{1}/4 and ^{1}/3; *POxy. astron.* 4179 (Jones 1999a, vol. 2, 188-191), from 348 CE, gives them to quarter-hour precision.

[6] Modern data from the JPL Horizons ephemeris, ssd.jpl.nasa.gov . To obtain approximate times in hours after midnight for Alexandria or Rhodes, add two hours to the UT times.

alternate observation	*about the 5th hour (of day), on ring at Alexandria*	
135 March 24	after midnight	March 24 05:15
128 March 23	about sunset	March 23 21:30

The alternate report for the vernal equinox of 146 BCE is the only one for which Ptolemy specifies the place of observation; he includes it to illustrate the discrepancy possible in observed equinox times. The "ring" was a circular ring of bronze erected in the plane of the equator in the Square Stoa at Alexandria, probably a form of equatorial sundial. According to Hipparchus, the time when the Sun crossed the equator could be observed as the time when the interior surface of the ring switched from being illuminated from the north to from the south or *vice versa*, if this happened during the daytime. Hence a precision of one hour was possible for diurnal equinoxes observed on the ring. Ptolemy's summary of the argument of *On the Shifting of the Solstitial and Equinoctial Points* makes it clear that Hipparchus cited several equinox timings from the bronze ring, but unfortunately this is the only one that Ptolemy saw fit to repeat.[7]

The rest of the reports are probably all to be attributed to Hipparchus himself, and the observations were presumably made on Rhodes.[8] The precision of the times is to the quarter day. One report (the autumnal equinox of 158 BCE) expresses the time as the 6th seasonal hour of day, but this is just a different way of saying noon. On the other hand, the time of the 135 BCE vernal equinox, given as "after midnight," is a qualitative nuancing of a scheme that otherwise can be understood as limiting the possible times to noon, midnight, 6 AM, and 6 PM.

The equinox times were obviously obtained by interpolation, in all probability from noon observations of the Sun's altitude using a meridian instrument comparable to the ones that Ptolemy describes in *Almagest* 1.12. Hipparchus would have noted the Sun's altitude (i.e. the center of the shadow of the horizontal gnomon) on successive days as it passed the point corresponding to the celestial equator. The following observational strategy would result in reported times exhibiting the precision attested in *Almagest* 3.1:

Case i. The altitude on day n is very near the equatorial point, with those on days $n-1$ and $n+1$ about equidistant from it. The time of equinox is considered to be noon of day n. If the altitude on day $n-1$ is *slightly* closer than that on day $n+1$, the time is considered to be "before noon," and conversely for "after noon."

Case ii. The altitudes on days n and $n+1$ are equidistant from the equatorial point. The time of equinox is considered to be midnight of the night between days n and $n+1$ If the altitude on day n is *slightly* closer than that on day $n+1$, the time is considered to be "before midnight," and conversely for "after midnight."

Case iii. The altitudes on days n and $n+1$ straddle the equatorial point, and that on day n is noticeably closer than that on day $n+1$, but not really close. The time of equinox is considered to be about sunset of day n.

Case iv. The altitudes on days n and $n+1$ straddle the equatorial point, and that on day $n+1$ is noticeably closer than that on day n, but not really close. The time of equinox is considered to be about daybreak of day $n+1$.

Since the daily change in the Sun's declination around the equinoxes is about 24', this strategy would be feasible on an equatorial instrument of plausible dimensions.

In the same chapter (Toomer 1984, 138) Ptolemy reports his own observations of the autumnal equinox of 139 CE (made "very securely," ἀσφαλέστατα) and of the vernal equinox of 140 CE; and in 3.7

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[7] On Ptolemy's highly elliptical summary of Hipparchus's book see Jones 2005a, 18-27.

[8] Most of the reports of Hipparchus's observations in the *Almagest* lack specification of the place of observation. An observation of a lunar eclipse in 141 BCE (*Almagest* 6.5, Toomer 1984, 284) and three observations of the Moon's elongation from the Sun in 128-127 BCE (*Almagest* 5.3, Toomer 1984, 224, and 5.4, Toomer 1984, 227 and 230) are expressly stated to have been made in Rhodes.

(Toomer 1984, 168) he gives his observation of the autumnal equinox of 132 CE ("one of those that were most accurately obtained"). Again we summarize:

132 September 25 (AE)	about 2 equinoct. hours after noon	Sept 24 02:30
139 September 26 (AE)	approx. 1 hour after sunrise	Sept 24 19:30
140 March 22 (VE)	approx. 1 hour after noon	March 21 14:15

These reports are well established as fabricated (Delambre 1817, vol. 1, xvi, and vol. 2, 107-114; Jones 2005a, 21). Ptolemy extrapolated the later pair from Hipparchus's autumnal equinox report of 147 BCE and the vernal equinox report of 146 BCE using Hipparchus's tropical year of 365 $^{1}/4$ – $^{1}/300$ days, and the report from 132, which Ptolemy uses to establish the solar epoch, was also constructed to be approximately consistent with the other reports and the assumed year length. Because Hipparchus's tropical year is slightly too long, all three times are more than a day too late.

It is interesting, and somewhat puzzling, that Ptolemy constructed these reports with a pretended one hour precision. As we have seen, such precision is in principle possible with an equatorial ring, but only if the moment of equinox is diurnal, and anyway Ptolemy has told us earlier in 3.1 that the equatorial rings that existed in Alexandria in his day were unreliable because they were distorted and out of correct alignment with the equator.[9] In fact, he says expressly that his solstice and equinox observations were carried out using the meridian instruments described in 1.12, and, as a general assessment, that both solstice and equinox observations made with any instrumentation are subject to errors of as much as a quarter day. These statements all appear within a few pages of each other, so that a reasonably attentive reader, alerted by Ptolemy himself to the issue of precision, is likely to realise that something is odd about his reports. The improvement of fit to Hipparchus's tropical year resulting from extrapolating the equinox times to one hour precision instead of quarter day precision is negligible.

According to Ptolemy (again in *Almagest* 3.1, Toomer 1984, 132-133), Hipparchus listed a number of successive observations of the times of both summer and winter solstices, and a verbatim quotation from the book tells us that some or all of these solstices were observed by Archimedes and by Hipparchus himself. Regrettably, Ptolemy chose not to repeat these reports. He gives us only two complete reports, of a summer solstice observed by "those around Meton and Euctemon" in 432 BCE and a summer solstice observed by himself in 140 CE (Toomer 1984, 138), as well as the interval of time between a pair of summer solstices observed by Aristarchus in 280 BCE and by Hipparchus in 135 BCE (Toomer 1984, 139). Like Ptolemy's equinox observations, his solstice of 140 CE is a fabrication, in this case extrapolated from the Meton-Euktemon 432 BCE solstice using Hipparchus's tropical year.

The dates and times of the solstices of 280 and 135 BCE can be restored with good probability on the assumption that a year length approximating $^{108478}/297$ days attested in a cuneiform tablet from Babylon is a parameter transmitted from a Greek source and derived from the assumed interval in days between the 432 and 135 BCE solstices divided by the 297 intervening years (Rawlins 1990; Jones 2005a, 23-24). In addition, an inscription and two papyri contain dated solstice reports: *IMilet* inv. 84 has the dates of the summer solstices of 432 and 109 BCE without indications of time (Diels & Rehm 1904); *PFouad* inv. 267 A, recto lines 11-12 has a report, unfortunately defectively copied, of a summer solstice observed by Hipparchus in 158 BCE (Fournet & Tihon 2014); and *PRylands* 1.27, lines 58-60 and 64, attributes dates to Ptolemy for both the summer solstice of 140 CE (with a variant time one hour earlier than the time reported in *Almagest* 3.1) and the winter solstice of the preceding year (Hunt 1911; Jones 1997, 34). The solstice reports in *PRylands* are spurious, however. They were obtained from the dates of Ptolemy's equinox observations of 139 and 140 CE, which the papyrus quotes accurately from the *Almagest*, assuming the exact intervals 94 $^{1}/2$ days from vernal equinox to summer solstice and 92 $^{1}/2$ days from summer solstice to autumnal equinox that Ptolemy gives in *Almagest* 3.4 as the date for deriving the parameters of his eccenter model for the Sun, and the exact intervals 88 $^{1}/8$ days and 90 $^{1}/8$ days for the intervals from autumnal equinox to winter solstice and from winter solstice to vernal equinox, which are *not* given in the *Almagest* but that can be derived from the eccenter model.

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[9] Britton 1992, 15-16 and 24-37 analyses theoretically the behavior of equatorial rings at equinoxes, showing that even with correct alignment there would be irregularities in the observed times. Ironically, the 146 BCE vernal equinox observation from the ring at Alexandria is not only more accurate than Hipparchus's but also the most accurate of all the equinox observations in the *Almagest*.

The seven solstice reports are summarized below, with restorations in square brackets and fabricated reports marked with an asterisk:

432 BCE June 27 (SS)	early morning	June 28 09:00
280 BCE [June 26] (SS)	[noon]	June 27 03:30
158 BCE June 26 (SS)	hour [*numeral missing*] of day	June 26 15:45
135 BCE [June 26] (SS)	[early morning]	June 26 05:30
109 BCE June 26 (SS)	[no time specified]	June 25 12:15
139 CE Dec. 24 (WS)*	hour 4 of day	Dec. 22 13:30
140 CE June 25 (SS)*	about 2 hours after midnight	June 23 12:00
*alternate (PRylands)**	*hour 7 of night*	

We have good reason to suppose that Hipparchus's solstice times too were reported to quarter-day precision. As was the case with the equinoxes, this precision would arise through applying a plausible strategy to solar noon altitudes observed with a meridian instrument. The first step is to observe the altitude on a day n something like ten days before the anticipated solstice, when the daily change in solar declination is still large enough to observe on the scale. Then one continues observing noon altitudes until, after the solstice, the altitudes approach and pass day n's altitude:

Case i. The altitude on day $n+k$ is approximately the same as the altitude on day n, such that k is even. The time of equinox is considered to be day $n+k/2$, noon.

Case ii. The altitude on day $n+k$ is approximately the same as the altitude on day n, such that k is odd. The time of equinox is considered to be midnight between days $n+(k-1)/2$ and $n+(k+1)/2$.

Case iii. The altitude on day n is about halfway between the altitudes on days $n+k$ and $n+k+1$, such that k is even. The time of equinox is considered to be day $n+k/2$, about sunset—strictly speaking, 6 PM.

Case iv. The altitude on day n is about halfway between the altitudes on days $n+k$ and $n+k+1$, such that k is odd. The time of equinox is considered to be day $n+(k+1)/2$, about daybreak—strictly speaking, 6 AM.

It would certainly be surprising if Hipparchus had used greater precision in reporting solstice times than times of equinoxes, when the Sun's declination is changing much more rapidly. Moreover, in the passage that Ptolemy quotes from *On the Shifting of the Solstitial and Tropical Points*, Hipparchus writes that the solstices observed by Archimedes and by himself were subject to timing errors up to a quarter day, though strictly speaking this is a statement about accuracy, not precision (Toomer 1984, 133). I think, therefore, that the missing hour number in *PFouad* must have stood for one of the quarter-day times, that is, daybreak, noon, or sunset.

The Meton-Euctemon solstice of 432 BCE and Aristarchus's of 280 BCE would seem at first glance to have been given to quarter day precision too, but this was probably not the case. The 432 BCE solstice was apparently not one of a series, but a one-off date used to calibrate a 19-year calendrical cycle, and the date was famous enough in antiquity to be reported also by the first century BCE historian Diodorus, who gives it according to the Athenian calendar, and by the author of the Miletus calendar inscription *IMilet* inv. 84, according to both the Athenian and Egyptian calendars, in both instances with no indication of a time of day.[10] The 280 BCE solstice, which we know of only from Ptolemy, was also a calibration date, since it falls in a year that is exactly eight 19-year "Metonic" cycles (or two 76-year "Callippic" cycles) after the 432 solstice (Dessau 1904). Ptolemy remarks concerning both solstices that the observations were determined "rather roughly" (ὁλοσχερέστερον εἰλημμένας, Toomer 1984, 137), adding that Hipparchus thought so too, and a little later he says again that the 432 solstice was "rather roughly recorded" (ὁλοσχερέστερον ἀναγεγραμμένην, Toomer 1984, 138).

The latter expression shows that the roughness was not just with respect to the method of observation but also involved the wording of the report. I think this has to mean that the times of the 432 and 280

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[10] Bowen & Goldstein 1988 argue against interpreting the Meton-Euctemon report as an observation of the solstice's date; but that is at least how Hipparchus and Ptolemy understood it.

solstices were not given to a precision comparable to the later observations of Archimedes and Hipparchus. In fact, both were probably transmitted as simple dates without any specification of time. The "daybreak" time that Ptolemy reports for the Meton-Euktemon solstice probably means that Hipparchus believed that it had been determined as the date when the Sun's rising point on the horizon was farthest north—a plausible hypothesis for this early stage of Greek astronomy, if it was not based on actual testimony (Hannah 2009, 8 and 56; Kourouniotes & Thompson 1932, 207-211)—so that one might hope that the true moment of solstice was within half a day of that sunrise. The noon time associated with the 280 solstice would likewise mean that Hipparchus believed that Aristarchus used a meridian instrument.

If this reconstruction is correct, then Archimedes, working later in the third century BCE, would have been the first person to employ interpolation methods to refine observations of solar phenomena to a precision of a fraction of a day. If we may judge by Hipparchus's preserved equinox reports, quarter day precision was actually a bit more refined than the accuracy of the observations justified: his autumnal equinoxes average about eight hours too late, and his vernal equinoxes about seven hours too early, perhaps reflecting a systematic error in his instruments that tended to underestimate his terrestrial latitude. No evidence exists that later astronomers in antiquity improved on either the precision or the accuracy of Hipparchus's solar observations; on the contrary, the fact that Ptolemy could assign dates to solstices and equinoxes in his own time that were consistently more than a day too late implies that he knew of no context of recent solar observations that even approached Hipparchus's in quality.

Timed observations of the planets and Moon

The solar observations discussed in the preceding section represent a special type of timed observation. Except for the times of diurnal equinoxes observed on an equatorial ring, of which only one specimen is preserved by Ptolemy, they did not involve a direct measurement of the time of day when the phenomenon occurred. Instead, observations were made only at a particular time of day, sunrise or noon, and either one selected the observation that came closest to representing the phenomenon—in which case there was no actual time determination more refined than to the nearest day—or one interpolated to estimate the exact moment of the phenomenon. These are not quite the only ancient observation reports for which the reported times were obtained by interpolation between actual observations that did not coincide with the phenomenon. The times of the oppositions of each of the superior planets to the mean Sun that Ptolemy uses to derive the eccentricities of his models for those planets were also ostensibly interpolated.[11]

With these exceptions, the timed reports that we have from Ptolemy and other Greek sources generally were, or at least profess to be, observations made at the stated times. Among them, the observations of planets' positions relative to fixed stars preserved in the *Almagest* have, for the most part, the least precise time indications, whether we are speaking of the third century BCE anonymous reports pertaining to Mercury, Mars, and Jupiter with dates expressed in the calendar of Dionysius or the second century CE reports pertaining to Mercury and Venus ascribed to Theon the mathematician or to Ptolemy himself.[12] In all these planetary reports, we are told merely that the observation was made in the evening (usually ἑσπέρας, "during the evening," but sometimes by qualifying the planet itself as ἑσπέριος, "as evening star") or in the morning (ὄρθρου, "at dawn," or ἑῷος, "as morning star"). The majority of Ptolemy's own reports indicate that the observation was made using his armillary astrolabe, which, as we will see, allowed one to read off the precise time when a star of known position was being sighted, so it would seem that he was deliberately maintaining a level of imprecision consistent with the reports he took over from past or contemporary astronomers.

In using the planetary reports for his theoretical purposes, Ptolemy had to replace these vaguely expressed times with times in equinoctial hours from noon. He does not state what these refined times were, but in principle they ought to be deducible from the computed longitudes of the mean Sun that he provides for each report. Fig. 1 plots the difference between these deduced times and 6 PM (for evening observations) or 6 AM (for morning observations) against the solar mean longitude. Interestingly, there is no detectable seasonal component in these differences that would reflect the variation in the length of day (or the equation of time, for that matter); it seems that Ptolemy basically assumed 6 PM for evening

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[11] The reports are in *Almagest* 10.7 (Toomer 1984, 484), 11.1 (Toomer 1984, 507), and 11.5 (Toomer 1984, 525).

[12] The reports are in *Almagest* 9.7-10 (Mercury), 10.1-4 (Venus), 10.9 (Mars), 11.3 (Jupiter), and 11.7 (Saturn). A report of an observation of Jupiter in 104 CE in the papyrus *POxy. astron.* 4133 (Jones 1999a, v. 2, 2-5) provides no time indication at all.

observations and 6 AM for morning ones, regardless of the time of year, while "fudging" the mean Sun by amounts seldom exceeding an hour's worth of motion so that his analyses would lead to the exact parameters that he wishes to demonstrate.

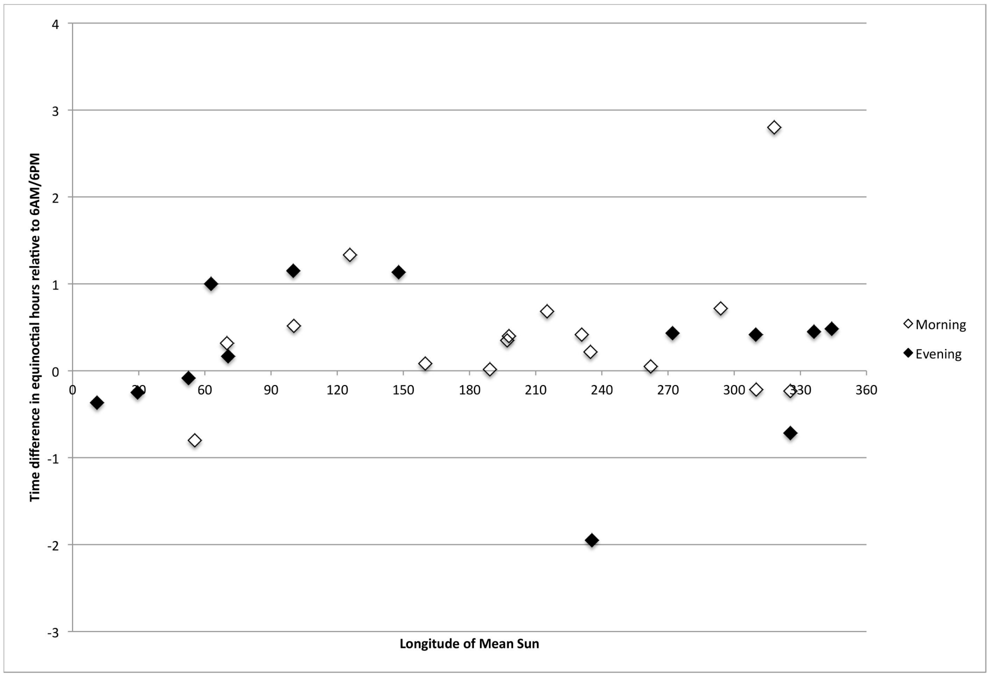

Fig. 1. Time differences relative to 6 AM/PM derived from the longitude of mean Sun in the planetary observation reports in the *Almagest*, plotted against the mean Sun. The data set includes all planetary observations in the *Almagest* timed simply as morning or evening.

The non-interpolated reports in the *Almagest* that have more precise times can be divided into those that Ptolemy claims to have made and those from his predecessors. Among the latter group, we may consider first the five observation reports of sightings of the Moon or Venus with fixed stars attributed to Timocharis (*Almagest* 7.3 and 10.4):

295 BCE December 21, "beginning of the 10th hour of night" (Toomer 1984, 337)

294 BCE March 9, "at the beginning of the third hour (of night)" (Toomer 1984, 335)

283 BCE January 29, "towards the end of the third hour (of night)" (Toomer 1984, 334)

283 BCE November 9, "when as much as half an hour of the tenth hour had passed" (Toomer 1984, 336)

272 BCE October 12, "at the twelfth hour" (Toomer 1984, 477)

Here, in the earliest surviving Greek observations timed to a small fraction of a day, we find what apparently persisted as a common practice in astronomy up to Ptolemy's time, the use of "nuanced" seasonal hours. The observations of Agrippa and Menelaus, from the late first century CE, use the same conventions (*Almagest* 7.3):

92 CE November 29, "third hour of night" (Agrippa, Toomer 1984, 334)

98 CE January 11, "when the tenth hour (of night) was finished" (Menelaus, Toomer 1984, 336-337)

98 CE January 14, "towards the end of the eleventh hour (of night)" (Menelaus, Toomer 1984, 338)

On the other hand, the time specifications—some of them obviously deduced rather than observed—in four anonymous Alexandrian reports of lunar eclipses (*Almagest* 4.11 and 6.5) show a more refined precision to fractions of hours:

201 BCE September 22, "the Moon began to be eclipsed half an hour before it rose, and its full light was restored in the middle of the third hour (of night)" (Toomer 1984, 214)

200 BCE March 19, "(the eclipse) began when 5 ^{1}/3 hours of night had passed" (Toomer 1984, 214)

200 BCE September 11, "(the eclipse) began when 6 ^{2}/3 hours of night had passed… mid eclipse took place at about 8 ^{1}/3 hours of night" (Toomer 1984, 215)

174 BCE May 1, "from the beginning of the eighth hour until the end of the tenth" (Toomer 1984, 283)

This is also the precision of Hipparchus's lunar observations (*Almagest* 6.5, 5.3, and 5.5):

141 BCE January 27, "at the beginning of the fifth hour (of night)… the Moon began to be eclipsed" (Toomer 1984, 284)

128 BCE August 5, "when ^{2}/3 of the first hour (of day) had passed" (Toomer 1984, 224)

127 BCE May 2, "at the beginning of the second hour" (Toomer 1984, 227)

127 BCE July 7, "at 9 ^{1}/3 hours (of day)" (Toomer 1984, 230)

What is particularly noteworthy about the pre-Ptolemy observations is that their times are all expressed in *seasonal* hours. We can be sure that this was the form in which Ptolemy found them, because in each instance he provides the conversion to equinoctial hours relative to midnight or noon as part of the analysis of the report. Now there is one type of ancient timing device that yielded times in seasonal hours as a matter of course, namely the sundial; and the times in Hipparchus's three diurnal lunar observations could have been read off an accurately constructed sundial. On the other hand, nocturnal time measurements, whether made by a water clock or by stellar observations, naturally lend themselves to uniform time units, and one has to go out of one's way, either by employing seasonal calibrations or by making a unit conversion subsequent to the measurement, to obtain seasonal hours. The effort is not great, perhaps, but one had to have a reason for making it.

One possible explanation of the use of seasonal hours for observation records is that the intended application of the observations was not the kind of astronomy in which calculation of exact time intervals was an important element, or even not astronomy at all. For example, an eclipse might have been observed primarily as an ominous event, for the interpretation of which seasonal hours would be the relevant unit according to the astrological tradition.[13] Hipparchus's use of seasonal hours is not so easy to account for,

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[13] Ptolemy, *Tetrabiblos* 2.7 states that the time-scale of the astrological consequences of an eclipse are to be determined according to the eclipse's duration in equinoctial hours, but this is presumably one of his "reforms."

except as a sign that the convention of stating times in seasonal hours was so firmly established that he kept to it despite the inconvenience for theoretical work.[14]

Following the equinoxes and solstices in Book 3 that we have already discussed, the next timed observations of his own that Ptolemy reports are three lunar eclipses in *Almagest* 4.6 (Toomer 1984, 191-192). He states only the times of mid-eclipse, which would have to have been found indirectly as the halfway point of either the entire eclipse or its totality, and he does not say how the times were determined:

133 CE May 6, 1 equinoctial hour before midnight
134 CE October 20, 1 equinoctial hour before midnight
136 CE March 6, 4 equinoctial hours after midnight

An unattributed eclipse report in *Almagest* 4.9 (Toomer 1984, 206) is expressed similarly, though the precision here is apparently finer:

125 CE April 5, 3 $^{3}/5$ equinoctial hours before midnight

Since this date is about two years earlier than the earliest observation that Ptolemy expressly takes credit for, it has been suggested that the observer may have been Theon the mathematician, whose identified reports are from the interval 127-132 CE (Toomer 1984, 206 note 54), but Ptolemy seems to be at least as likely a candidate (Britton 1992, 51 note 7). In the case of the three eclipses from 133-136 CE, the exactness with which the reported times lead *via* a highly sensitive method of analysis to the value for the lunar epicycle radius that Ptolemy wishes to demonstrate gives rise to suspicion that at least one of the times was tampered with.[15]

In *Almagest* 5.1 (Toomer 1984, 217-219) Ptolemy describes the construction and use of his armillary astrolabe (an instrument that has practically nothing in common with the planar astrolabe now usually designated by the term), and most of his precisely timed observations in the rest of the treatise are supposed to have been made by its means.[16] The armillary comprised a set of rings representing an ecliptic frame of reference (tropical longitude and latitude) inset within a ring representing an equatorial frame of reference that in turn was inset within a meridian ring. The principle of operation was that one would manipulate the ecliptic system of rings so that it is aligned with the actual ecliptic at the time of observation, and then by lining up a movable sight with the desired heavenly body, one could read its longitude and latitude off the graduations on the rings. The alignment was performed by determining the longitude and latitude of a reference body, say the Sun or a fixed star, from tables and lining up this position as marked on the rings' graduations with the actual body by sight. Since one could also read off the degree of the ecliptic that was crossing the meridian at the time of observation, one could easily obtain the time in equinoctial hours from noon or midnight from the difference between the culminating longitude and the Sun's right ascension calculated from tables.

Curiously, the reports with precise times of observations made using the armillary all fell within an interval of a little more than half a year (*Almagest* 5.3, 7.2, 9.11, and 10.4). In each case Ptolemy gives us not only the deduced time in equinoctial hours, to quarter-hour precision in many if not all cases, but also the data from which it was determined, namely the computed longitude of the Sun and the observed culminating degree of the ecliptic.

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[14] Similarly, all but two of the Babylonian eclipse reports in the *Almagest* have their times reported in seasonal hours, where the original documents presumably expressed them as equinoctial time-degrees (UŠ) counted from sunset or sunrise (Britton 1992, 50-51); it would have been equally easy, and much more convenient for astronomical work, to convert the Babylonian times to equinoctial hours counted from midnight. The Babylonian eclipse report from 502 BCE (*Almagest* 4.9) gives the time of mid eclipse as 6 $^{1}/3$ equinoctial hours past sunset, which appears to be an almost direct translation of the Babylonian timing with a simple change of unit according to the equation 1 equinoctial hour = 15 UŠ. The report from 523 BCE in *Almagest* 5.14 gives the time of mid eclipse as one hour before midnight without specifying which kind of hour, though in his analysis of the eclipse Ptolemy treats it as one equinoctial hour.

[15] Newton 1977, 122-123. There may be some significance in the fact that the times that Ptolemy gives for the first two of the set are quite accurate while the third is more than half an hour off (Steele 102-103).

[16] The one exception is in *Almagest* 5.13 (Toomer 1984, 247), an observation on 135 CE October 1 of the zenith distance of the Moon when it was crossing the meridian. The time, which is reported as 5 $^{5}/6$ equinoctial hours after noon, might have been determined by the armillary or from a sundial, but the measurement itself was reportedly performed using Ptolemy's parallactic instrument.

138 CE December 16, 4 $^{3}/4$ equinoctial hours after midnight
Sun at Sagittarius 23°, Virgo "second degree" culminating
Observation of Venus relative to star (*Almagest* 10.2, Toomer 1984, 474)

138 CE December 22, 4 equinoctial hours before midnight
Mean Sun at Sagittarius 28° 41', Aries "last degree" culminating
Observation of Saturn relative to star (*Almagest* 11.6, Toomer 1984, 538)

139 CE February 9, 5 $^{1}/4$ equinoctial hours before noon
Sun at Aquarius 18 $^{5}/6$ °, Sagittarius 4° culminating
Observation of Moon relative to Sun (*Almagest* 5.3, Toomer 1984, 223)

139 CE February 23, 5 $^{1}/2$ equinoctial hours after noon
Sun at Pisces 3°, Taurus "last degree" culminating
Observation of Moon relative to Sun (*Almagest* 7.2, Toomer 1984, 328)

139 CE February 23, 6 equinoctial hours after noon
Gemini "first quarter" culminating
Observation of star relative to Moon (*Almagest* 7.2, Toomer 1984, 328)

139 CE May 17, 4 $^{1}/2$ equinoctial hours before midnight
Sun at Taurus 23°, Virgo "twelfth degree" culminating
Observation of Mercury relative to star (*Almagest* 9.10, Toomer 1984, 461)

139 CE May 30, 3 equinoctial hours before midnight
Mean Sun at Gemini 5° 27', Libra "twentieth degree" culminating
Observation of Mars relative to star (*Almagest* 10.8, Toomer 1984, 499)

139 CE July 11, "about" 5 equinoctial hours after midnight
Mean Sun at Cancer 16° 11', Aries "second degree" culminating
Observation of Jupiter relative to star (*Almagest* 11.2, Toomer 1984, 520)

When Ptolemy reports longitudes of heavenly bodies observed on the armillary, they are generally given to a precision of $^{1}/12$ °.[17] By way of contrast, the culminating degrees have only a 1° precision, a point emphasized by his use of ordinal numbers (as if all he could be sure of was that the culminating point was between two degree graduations) and the expression "first quarter", which apparently means a point about 7 $^{1}/2$ ° from the beginning of the zodiacal sign. This is explicable, since the graduated ecliptic ring was not in contact with the meridian ring. In accordance with the imprecision of the culminating degree, Ptolemy also often refrains from giving the computed mean or true solar longitude to the full precision (1') that his tables allowed. Since one degree of right ascension corresponds to $^{1}/15$ equinoctial hour, the quarter-hour precision of his stated times is actually rougher than his data would seem to have allowed, but probably realistic in relation to the accuracy of the determinations in practice.

As noted already, the sets of three oppositions of each of the three superior planets to the mean Sun from which Ptolemy determines the eccentricities and apsidal lines of his models were, he says (*Almagest* 10.7, Toomer 1984, 484), obtained by interpolation from observations made using the armillary. The procedure ought to have been something like this: he observed the planet's longitude on successive days near the expected opposition, recording the times of the observations as determined from the culminating degree of the ecliptic, and then interpolated to find the moment when the planet would have been diametrically opposite the mean Sun as computed from the tables. Although this ought to have allowed him

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[17] Exceptionally, one of his observed longitudes of Mercury (*Almagest* 9.8, Toomer 1984, 454) is given as Virgo 20 $^{1}/5$ °.

to obtain the times to a precision of a fraction of an hour, the reports consistently give the times as whole numbers of equinoctial hours from midnight or noon.[18]

A small number of timed observation reports survive from after Ptolemy. Theon of Alexandria precedes his calculations of the circumstances of the lunar eclipse of 364 CE June 16 according to Ptolemy's *Almagest* and *Handy Tables* with a set of reported times that he says he observed "very securely" (ἀσφαλέστατα, a term lifted from Ptolemy's characterization of his own solar observations in *Almagest* 3.1):

beginning of eclipse: 2 $^5/6$ seasonal hours after noon
mid eclipse: 3 $^4/5$ seasonal hours after noon
end of eclipse: 4 $^1/2$ seasonal hours after noon

However, since these times, while being about half an hour too early compared to the actual times of this eclipse, agree exactly with the times that he subsequently calculates from the *Almagest* tables, we have to conclude that Theon has picked up a bad habit from Ptolemy and fabricated his observations.[19] Among a set of miscellaneous observation reports collected by the Neoplatonist philosopher Heliodorus, we find an assortment of timings:[20]

498 CE May 1, apparent conjunction of Mars and Jupiter at "2nd hour of night"

503 CE February 21, lunar occultation of Saturn beginning "at approximately the 4th hour," and ending at "5 $^3/4$ seasonal hours" determined "from the astrolabe"

509 CE March 11, Moon near Aldebaran "after lamp-lighting"

509 CE June 13, apparently conjunction of Mars and Jupiter "after sunset"

At this late date "astrolabe" could have meant either an armillary or a planar astrolabe.[21] In any event, these observations seem to have been didactic exercises or spot-checks of the accuracy of the available astronomical tables, not part of a systematic program of astronomical research, and the precision of their time measurements was at best where Ptolemy had left it.

The significance for astrology of precision in astronomical observations

In all likelihood few Greco-Roman astrologers read the theoretical astronomical literature on which their tables were based; but if any of them did, what might they have inferred about the usefulness of the tables for time-sensitive astrological prognostications? It is impossible for us to answer this question at a general level because the only relevant specimen of the theoretical literature available to us is the *Almagest*.

If we limit our consideration to that work, we see a broad tendency for the times in the observation reports to become more precise at later periods, culminating in Ptolemy's claimed one hour precision for solstices and equinoxes and quarter-hour precision for times observed on the armillary. Moreover, Ptolemy makes a particular show of care about time precision in the observations from his own time that establish the epoch and long-term periodicities of his models, for example by applying a correction for equation of

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[18] *Almagest* 10.7 (Toomer 1984, 484), 11.1 (Toomer 1984, 507), and 11.5 (Toomer 1984, 525). The time of the first of the three oppositions of Saturn, 127 CE March 26, is stated to be "at eve" (ἑσπέρας), but this is treated subsequently as 6 equinoctial hours before midnight.

[19] Steele 2000, 103-104; Jones 2012. When I wrote the latter note I was unaware of the agreement of the ostensibly observed times with Theon's *Almagest* computations; I am indebted to Raymond Mercier (personal communication, October 19, 2012) for drawing this to my attention. So far as I know, all published literature relating to this report either treats it as genuine or denies that Theon claimed to have observed the times.

[20] Jones 2005b, 80-83.

[21] Neugebauer 1975, v. 3, 1040 argues that Heliodorus's instrument must have been a planar astrolabe "because only its design provides us with seasonal hours." This is not correct, however, since one can obtain seasonal hours from midnight or noon in the same way as equinoctial hours using an astrolabe, the only difference of procedure being that instead of using 15° as the ascensional equivalent of one equinoctial hour, one takes the ascensional equivalent of a seasonal hour, which is easily found e.g. from the table of right ascensions in the *Handy Tables*.

time to the critical observations for Mercury (*Almagest* 9.10, Toomer 1984, 461 with note 93) and Venus (*Almagest* 10.4, Toomer 1984, 474-475 with note 15). Our imaginary astrologer-reader would probably feel justified in trusting the predictions from Ptolemy's models and tables to be valid for astrological applications that assume one hour precision, but the possibility of further refinements would appear doubtful.

The picture that we get of astrological practice from the papyri as well as from texts transmitted through the medieval tradition is that Ptolemy's tables, in particular the *Handy Tables*, had come into widespread use already in the third century CE, and by the fifth century they had the field practically to themselves. The *Almagest* probably contributed significantly to the success of the tables, by establishing their credibility with a few influential astrologers whose word or example influenced the larger community of practitioners who had no direct contact with astronomical theory. Like the *Almagest*'s ostensibly rigorous deductive logic, the work's show of observational time precision must have been a key argument for the superiority of Ptolemy's astronomy.

References

Baccani, D. (1992), *Oroscopi greci: documentazione papirologica.* Ricerca papirologica 1. Messina: Sicania.

Bowen, A. C., and Goldstein, B. R. (1988), "Meton of Athens and Astronomy in the Late Fifth Century B.C.", in Leichty, E., Ellis, M. de J., and Gerardi, P. (eds.), *A Scientific Humanist: Studies in Memory of Abraham Sachs*. Philadelphia: University Museum, 39-81.

Britton, J. P. (1992), *Models and Precision: The Quality of Ptolemy's Observations and Parameters*. New York: Garland.

Delambre, J. B. J. (1817), *Histoire de l'astronomie ancienne*. 2 vols. Paris: Courcier.

Dessau, H. (1904), "Zu den milesischen Kalendarfragmenten", *Sitzungsberichte der Königlich-Preussischen Akademie Akademie der Wissenschaften, Phil.-hist. Kl.* 23: 266-268.

Diels, H., and Rehm, A. (1904), "Parapegmenfragmente aus Milet", *Sitzungsberichte der Königlich-Preussischen Akademie Akademie der Wissenschaften, Phil.-hist. Kl.* 23: 92-111.

Fournet, J.-L., and Tihon, A. (2014), *"Conformément aux observations d'Hipparque": le papyrus Fouad inv. 267 A*. Publications de l'Institut orientaliste de Louvain 67. Louvain-la-Neuve: Université catholique de Louvain, Institut orientaliste.

Hannah, R. (2009), *Time in Antiquity.* London: Routledge.

Hunt, A. S. (1911), *Catalogue of the Greek and Latin Papyri in the John Rylands Library. Vol. I: Literary Texts (Nos. 1-61)*. Manchester: University Press.

Jones, A. (1997), "Studies in the Astronomy of the Roman Period I. The Standard Lunar Scheme", *Centaurus* 39: 1-36.

Jones, A. (1999a), *Astronomical Papyri from Oxyrhynchus.* 2 vols. in 1. American Philosophical Society, Memoirs 233. Philadelphia: American Philosophical Society.

Jones, A. (1999b), "A Classification of Astronomical Tables on Papyrus", in Swerdlow, N. M. (ed.), *Ancient Astronomy and Celestial Divination*. Cambridge, Mass.: MIT Press, 299-340.

Jones, A. (2005a), "'In order that we should not ourselves appear to be adjusting our estimates… to make them fit some predetermined amount", in Buchwald, J. Z., and Franklin, A. (eds.), *Wrong for the Right Reasons*. New York: Springer, 17-39.

Jones, A. (2005b), "Ptolemy's *Canobic Inscription* and Heliodorus' Observation Reports", *SCIAMVS* 6: 53-97.

Jones, A. (2012), "Theon of Alexandria's Observation of the Solar Eclipse of A.D. 364 June 16", *Journal for the History of Astronomy* 43: 117-118.

Kourouniotes, K., and Thompson, H. A. (1932), "The Pnyx in Athens: A Study based on excavations conducted by the Greek archaeological service", *Hesperia* 1: 96-217.

Neugebauer, O., and van Hoesen, H. B. (1959), *Greek Horoscopes.* American Philosophical Society, Memoirs 48. Philadelphia: American Philosophical Society.

Neugebauer, O. (1975), *A History of Ancient Mathematical Astronomy.* 3 vols. Berlin: Springer.

Newton, R. R. (1977), *The Crime of Claudius Ptolemy.* Baltimore: Johns Hopkins Press.

Parker, R. A. (1959), *A Vienna Demotic Papyrus on Eclipse- and Lunar-Omina*. Providence: Brown University Press.

Rawlins, D. (1990), "Hipparchos' ultimate solar orbit & the Babylonian tropical year", *Dio* 1(1): 49-66.

Rochberg-Halton, F. (1988), *Aspects of Babylonian Celestial Divination: The Lunar Eclipse Tablets of Enūma Anu Enlil.* Archiv für Orientforschung, Beiheft 22. Horn: Ferdinand Berger & Söhne.

Rochberg, F. (1998), *Babylonian Horoscopes.* American Philosophical Society, Transactions 88.1. Philadelphia: American Philosophical Society.

Steele, J. M. (2000), *Observations and Predictions of Eclipse Times by Early Astronomers.* Archimedes 4. Dordrecht: Springer.

Toomer, G. J. (1984), *Ptolemy's Almagest.* London: Duckworth.