Journal of Astronomical History and Heritage, 23(1), 47–62 (2020).

ASTRONOMICAL DATING OF SEVEN CLASSICAL GREEK ECLIPSES

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Abstract: Solar eclipses described by seven ancient Greek writers are dated using our recent knowledge of their precise paths and physical appearance. From a list of the possible eclipses, we make five definite and two very likely identifications of the exact dates of the eclipses. We conclude that all seven writers were indeed alluding to eclipses, and our deduced dates corroborate those generally accepted by historians.

Keywords: eclipses, Earth rotation, ancient Greece

1 INTRODUCTION

Total—and sometimes annular—solar eclipses are spectacular and memorable events. The paths of totality and annularity are narrow and they occur infrequently at any one place. It is likely that no more than two, or possibly three, will be witnessed in the lifetime of an individual. There are three basic parameters involved in identifying an eclipse from a historical record: the date, place, and whether or not the eclipse was central (either total or annular) or partial. If someone in antiquity recorded that an event was associated with the sighting of an eclipse, it might be possible to identify the particular eclipse and hence the date and place of the event. The report of the eclipse needs to be substantiated by a comment such as ‘day turned to night’ or ‘stars appeared’, in order to be sure that the witness was actually in or near the relatively narrow path of totality or annularity, rather than somewhere in the large surrounding area of the partial eclipse. However, in some instances a comment such as ‘assumed the shape of a crescent’ indicates that the observer was close to the path of a large eclipse, and this may be sufficient to identify the eclipse.

Several accounts of total or large solar eclipses have come down to us from writers in ancient Greece. These include the writers Archilochus, Herodotus, Pindar, Thucydides, Xenophon, Diodorus and Plutarch, whose works span the seventh century BC to the first century AD. These accounts have been investigated extensively in the past by authors such as Ginzel (1899), Fotheringham (1920), Newton (1970) and Stephenson (1997). Recent knowledge of the behaviour of the Earth’s variable rate of rotation (Stephenson et al., 2016) gives us the advantage over previous investigators of being able to predict the paths of totality with greater accuracy. This gives us more confidence in deciding which eclipses were being referred to in the ancient Greek texts, and thus assigning a firm date and possible place of observation.

Fotheringham used five of the eclipses investigated here in his famous paper of 1920, where he derived a solution for what he termed the secular accelerations of the Sun and Moon. The secular acceleration of the Sun is now treated as the tidal retardation of the Earth’s spin. We compare and contrast the details of his identifications with ours.

2 CALCULATION OF ECLIPSE TRACKS

We have developed our own programs for the calculation and plotting of the eclipse tracks. The basic coordinates of the Sun and Moon are extracted from the Jet Propulsion Laboratory’s long-term ephemerides DE 431 (Folkner et al., 2008) and the algorithms for finding their positions for the particular date and time and the position of the track of the eclipse on the Earth are taken from *The Explanatory Supplement* (HMSO, 1961; Seidelmann and Urban, 2012), together with routines from the International Astronomical Union’s Standards of Fundamental Astronomy (SOFA, 2018). The map outlines were downloaded from Natural Earth at naturalearthdata.com.

3 THE PARAMETER ΔT

The cumulative error in time due to the variable rotation of the Earth is denoted by the parameter ΔT, which is the difference in time between a uniform time-scale (Ephemeris Time, now termed Terrestrial Dynamical Time) and the time-scale (Universal Time) measured by the Earth's rotation. The values of ΔT (seconds of time) used in our analysis are taken from the paper by Morrison et al. (2020). These are also available from HM Nautical Almanac's website, where these data on 'Earth Rotation - Change in the Length of Day' are listed (http://astro.ukho.gov.uk/nao/lvm/). A change in our adopted value of ΔT of +1 second produces a displacement in longitude of 0.25 arc minutes east in the position of the eclipse on the Earth's surface.

Table 1: Places (in degrees and minutes of arc) of places associated with the texts under consideration.

Location	Latitude (N)		Longitude (E)	
	°	′	°	′
Athens	37	59	23	43
Chaeronea	38	31	22	51
Paros	37	05	25	09
Rome	41	54	12	30
Syracuse	37	04	15	17
Thasos	40	46	24	43
Thebes	38	19	23	19

4 SEVEN ANCIENT GREEK TEXTS

We discuss chronologically the following seven texts, which have accounts or putative descriptions of solar eclipses:

(1) Archilochus:	BC 648 April 6
(2) Herodotus:	BC 585 May 28
(3) Pindar:	BC 363 April 30
(4) Thucydides:	BC 431 August 3
(5) Xenophon:	BC 394 August 14
(6) Agathocles:	BC 310 August 15
(7) Plutarch:	AD 71 March 20

The eclipses of BC 431, BC 310 and AD 71 were recognised as being eclipses by the original writers themselves, the true cause of eclipses having been explained by Anaxagoras ca. BC 450. Before that the cause was unknown to the original writer. Although in the cases of BC 585 and BC 394, the later writers Pliny and Plutarch, respectively, used the term 'eclipse' in their reports of these events. The geographical co-ordinates of the places mentioned in the following seven Subsections are listed above in Table 1.

4.1 Archilochus: BC 648 April 6

In one of his poems, the early Greek poet, Archilochus (ca. BC 680–645), included the following passage:

> Nothing can be surprising any more or impossible or miraculous, now that Zeus, father of the Olympians has made night out of noonday, hiding the light of the gleaming Sun, and … fear has come upon mankind. After this, men can believe anything … (Archilochus, fragment 122; trans. Barron and Easterling, 1985: 127).

This description strongly suggests that the eclipse was either total or nearly so. According to Barron and Easterling (1985: 117–119) Archilochus was the first Greek writer to take his material from what he claimed to be his own experience, rather than the stock of traditions. It is likely that he observed the eclipse himself. Therefore, we consider all the eclipses that occurred in his lifetime, in or near the places where he was living.

Archilochus was born on the island of Paros, south of mainland Greece. Later he moved to the nearby island of Thasos (see Figure 1). After occasional travels, he eventually returned to Paros, where he was later killed helping to defend the island. Although the precise dates of his birth and death are unknown, we know that he was a contemporary of King Gyges of Lydia (ca. BC 687 to 652), as mentioned in one of Archilochus' other poems and also asserted by Herodotus (I, 12). Five total solar eclipses occurred in and around Greece in the period BC 691 to 637, but only the eclipses of BC 657 April 15 and BC 648 April 6 produced totality in the region near Thasos/Paros. The eclipse of BC 657 passed considerably to the east of the region, and is eliminated from further consideration. We calculate that the eclipse of BC 648 passed over Thasos and just to the north of Paros, as displayed in Figure 1. Although the path of totality passed over Thasos, we cannot rule out totality at Paros because of the uncertainty in the adopted value of ΔT (19190s) at this epoch. The path could be shifted eastwards towards Paros by 0.7 degrees of longitude if ΔT were increased by about 170s. This is feasible given the uncertainty of the defining upper limit of ΔT around the epoch BC 700, which was determined using a Babylonian report that the Moon set eclipsed in BC 694 April 30/May 1 (Stephenson et al., 2016).

It is very likely that Archilochus was referring to the total, or almost total, eclipse of BC 648 April 6, which he probably observed from Thasos, or perhaps Paros. Fotheringham (1920: 107) used the geographical limits imposed by these two islands to constrain the position of the eclipse shadow in his investigation. However, his constraints were quite wide because the width was defined by the possibility that Thasos was on the southern edge of totality, or Paros was on the northern edge. For this reason, this eclipse did not contribute materially to his famous diagrammatic solution (Fotheringham, 1920: 123). From Figure 1, we see that the track of totality followed

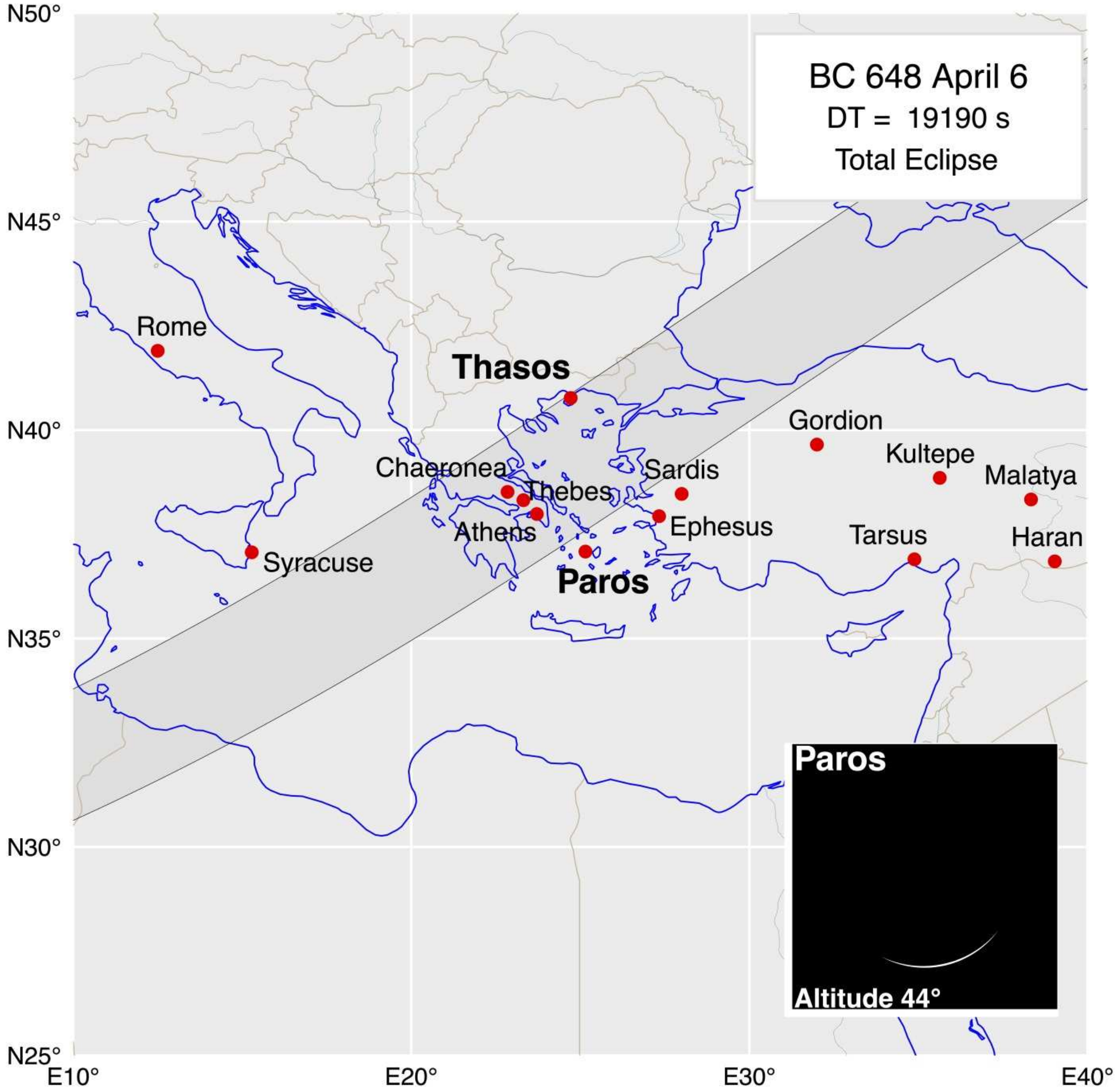

Figure 1: Track of the total eclipse of BC 648 April 6, showing the greatest coverage of the Sun as seen from Paros: total at Thasos (Catherine Hohenkerk, map outline from Natural Earth).

the mean position of these two extremes.

4.2 Herodotus: BC 585 May 28

Herodotus (ca. BC 484–425) alluded to the interruption of a battle in Asia Minor between the Lydians and Medes due to a marked loss of dalight:

> After this, seeing that Alyattes would not give up the Scythians to Cyraxes at his demand, there was war between the Lydians and the Medes five years ... They were still warring with equal success, when it chanced, at an encounter which happened in the sixth year, that during the battle the day was turned to night. Thales of Miletus had foretold this loss of daylight to the Ionians, fixing it within the year in which the change did indeed happen. So when the Lydians and Medes saw the day turned to night they ceased from fighting, and both were zealous to make peace. (Herodotus I, 74; trans. Godley, 1920).

Although Herodotus does not give an explanation of what caused the darkness by day, his allusion to its prediction by Thales indicates that the phenomenon was an eclipse of the Sun.

The first century AD Roman author Pliny in his *Naturalis Historia* (II: 53) gives additional details. Pliny does not mention the battle, but he confirms that the event occurred during the reign of Alyattes and further specifies the year that the eclipse occurred, both in terms of the Greek and Roman eras:

> Miletus, who in the fourth year of the 48th Olympiad (BC 585/4) foretold the eclipse of

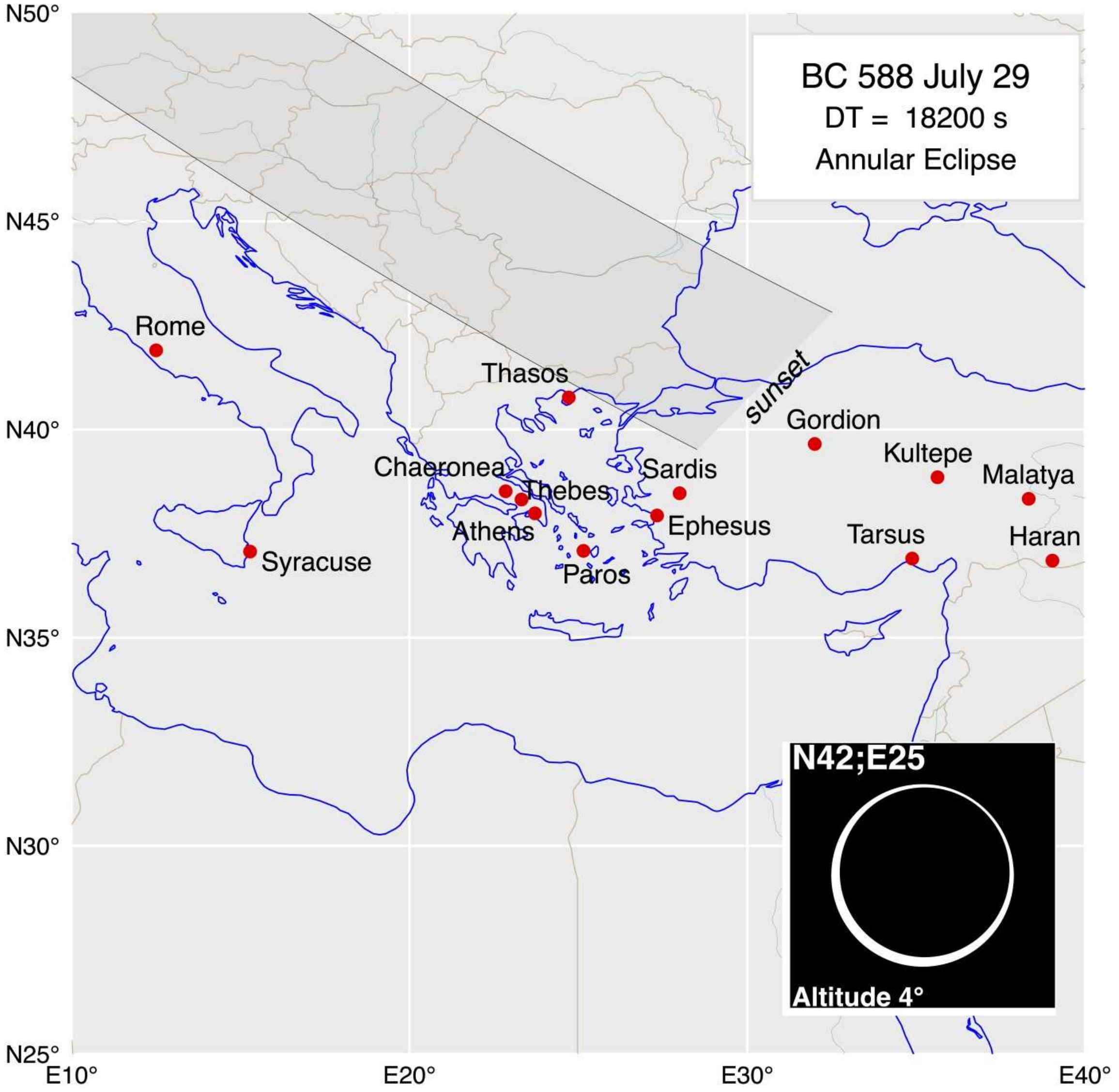

Figure 2: Track of the annular eclipse of BC 588 July 29. The inset shows the annulus at greatest coverage of the Sun's disk at a point in the track. Elsewhere more of the Sun was visible (Catherine Hohenkerk, map outline from Natural Earth).

> the Sun that occurred in the reign of Alyattes, in the 170th year after the foundation of Rome (BC 584/3). (Pliny, trans. Rackham, 1938).

Only the paths of the eclipses of BC 588 July 29 and BC 585 May 28 crossed Asia Minor in the period BC 590 to 580, which allows for some uncertainty in Pliny's date. The annular eclipse of BC 588 July 29 can be discounted because the eclipse path only touched the extreme north-western tip of Asia Minor as the Sun was setting, and it was night-time in the rest of Asia Minor (see Figure 2). This could not have been described as "… day was turned to night …", especially since calculation shows that at least 13% of the Sun's disk remained uncovered in Asia Minor, even in the central zone of annularity in the northwest.

Figure 3 shows the calculated track of totality in BC 585 May 28, which agrees with Pliny's date. The eclipse occurred late in the afternoon in Asia Minor, where the battle took place. In the absence of any other viable eclipses around this date in Asia Minor, we conclude that Herodotus was referring to this eclipse, and that the track of totality in Figure 3 defines the corridor in Asia Minor in which the battle took place. Fotheringham (1920) concluded that the battle could have been fought almost anywhere in Asia Minor. Our solution is more specific, and, in particular eliminates the NE region of Asia Minor.

4.3 Pindar: BC 463 April 30

In one of his poems Pindar (ca. BC 518–438) begins with a direct mention of the Sun:

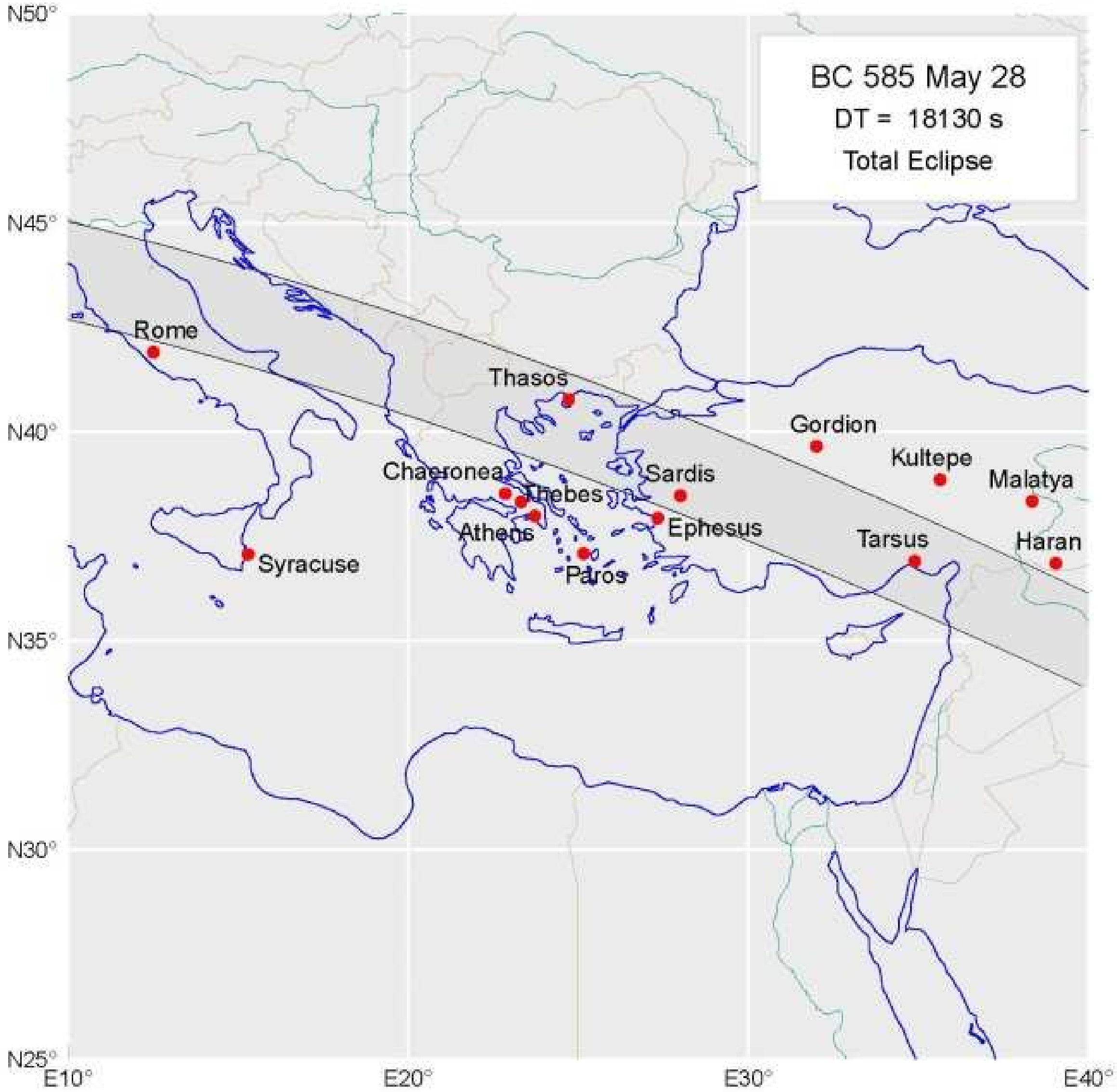

Figure 3: Track of the total eclipse of BC 585 May 28. A battle between the Lydians and Medes took place in Asia Minor, somewhere in the track of totality (Catherine Hohenkerk, map outline from Natural Earth).

> Beam of the Sun!
> O thou that seest from afar, what wilt thou be devising?
> O mother of mine eyes!
> O star supreme, reft from us (klepto-menon) in the daytime!
> Why hast thou perplexed the power of man and the way of wisdom by rushing forth on a darksome track ...
> Change this worldwide portent into some painless blessing for Thebes.
> (Pindar, Paean ix; trans. Sandys, 1915: 547–549).

We interpret this as a description of a total, or nearly total, solar eclipse.

Pindar, who was born in a village near Thebes, addressed his poem to the Thebans. Scholars are agreed that he wrote his earliest ode in BC 498 and his last in BC 446 (cf. Race, 1986: 1). Bowra (1964: 83–84; 378–379) in his book on Pindar, noting the sense of urgency in his ode, was in no doubt that Pindar witnessed the eclipse.

The dates of large solar eclipses visible in Greece during the period of his odes are:

BC 493 November 24	total
BC 488 September 1	annular-total
BC 478 February 17	annular
BC 463 April 30	total

4.3.1 The Eclipse of BC 493 November 24

This can easily be eliminated, because our calculations show that at least 20% of the Sun's disk remained uncovered at Thebes, and the sky

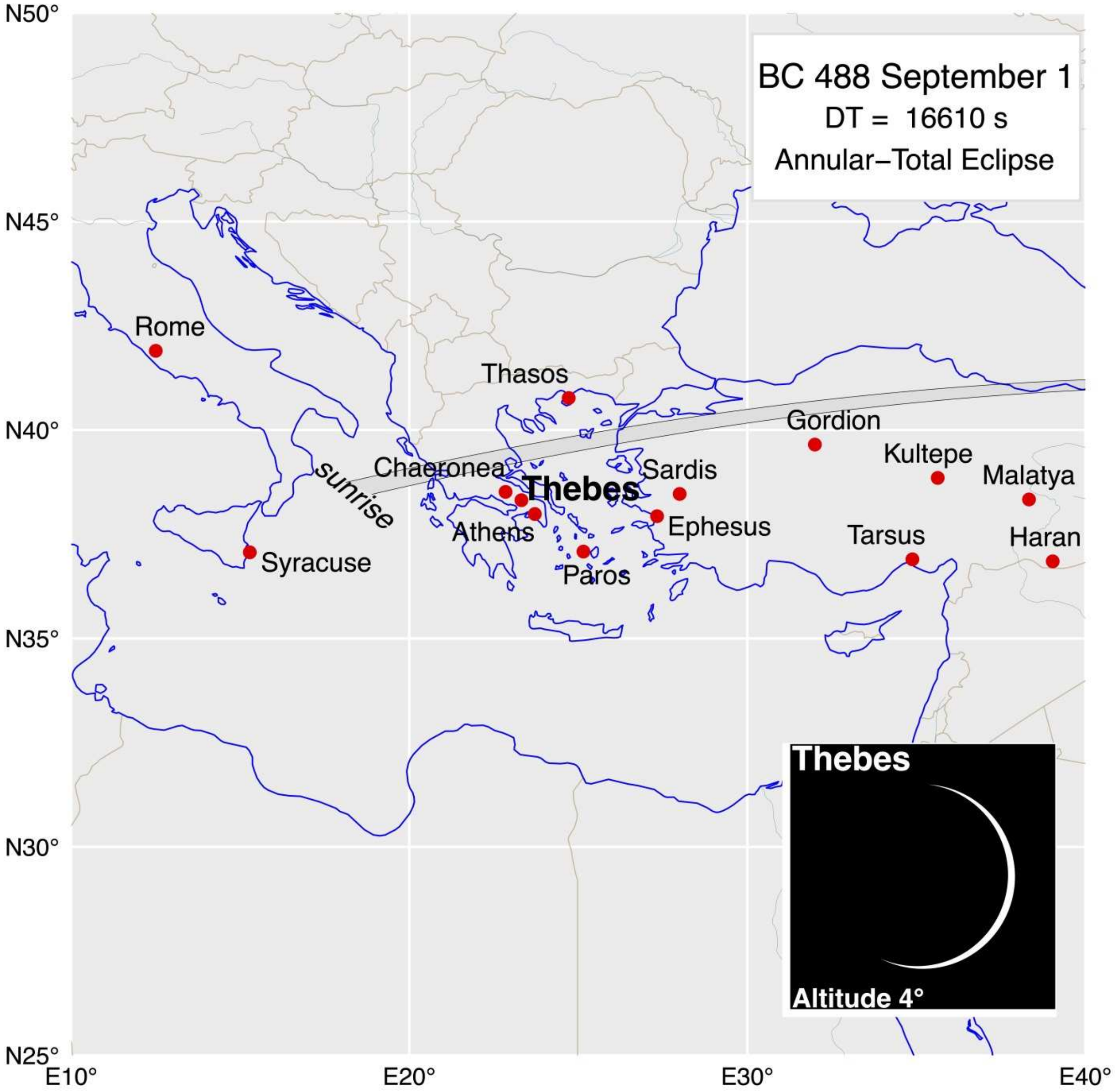

Figure 4: Track of the annular-total eclipse of BC 488 September 1. The inset shows the greatest coverage of the Sun's disk visible at Thebes soon after dawn (Catherine Hohenkerk, map outline from Natural Earth).

would not have been darkened noticeably.

4.3.2 The Eclipse of BC 488 September 1

The greatest phase at Thebes occurred just after sunrise, at a solar altitude of 4° (see Figure 4), when about 4% of the Sun's disk was uncovered. This would have seemed like a protracted dawn, rather than a loss of day-light during the day.

4.3.3 The Eclipse of BC 478 February 17

Even though this annular eclipse was central at Thebes (see Figure 5), at least 11% of the disk remained uncovered at maximum phase, and the sky would always have been quite bright. It probably can also be eliminated for this reason.

4.3.4 The Eclipse of BC 463 April 30

Figure 6 shows that the belt of totality passed just to the north of Thebes. It could not have been total at Thebes because the track ran almost parallel to the Earth's equator and no plausible adjustment of the Earth's rotation (ΔT) could bring Thebes under the track. At maxmum phase at around 2.30 pm local time 1% of the solar disk was uncovered (see inset). Therefore, the sky would never have been completely dark. Nevertheless, it would have been sufficiently dark to produce an eerie atmosphere, and hence give rise to Pindar's hyperbole. In northern Greece the eclipse was total, and since Pindar described the eclipse as a "… worldwide portent …" it is possible that he may have obtained one or more accounts from places within

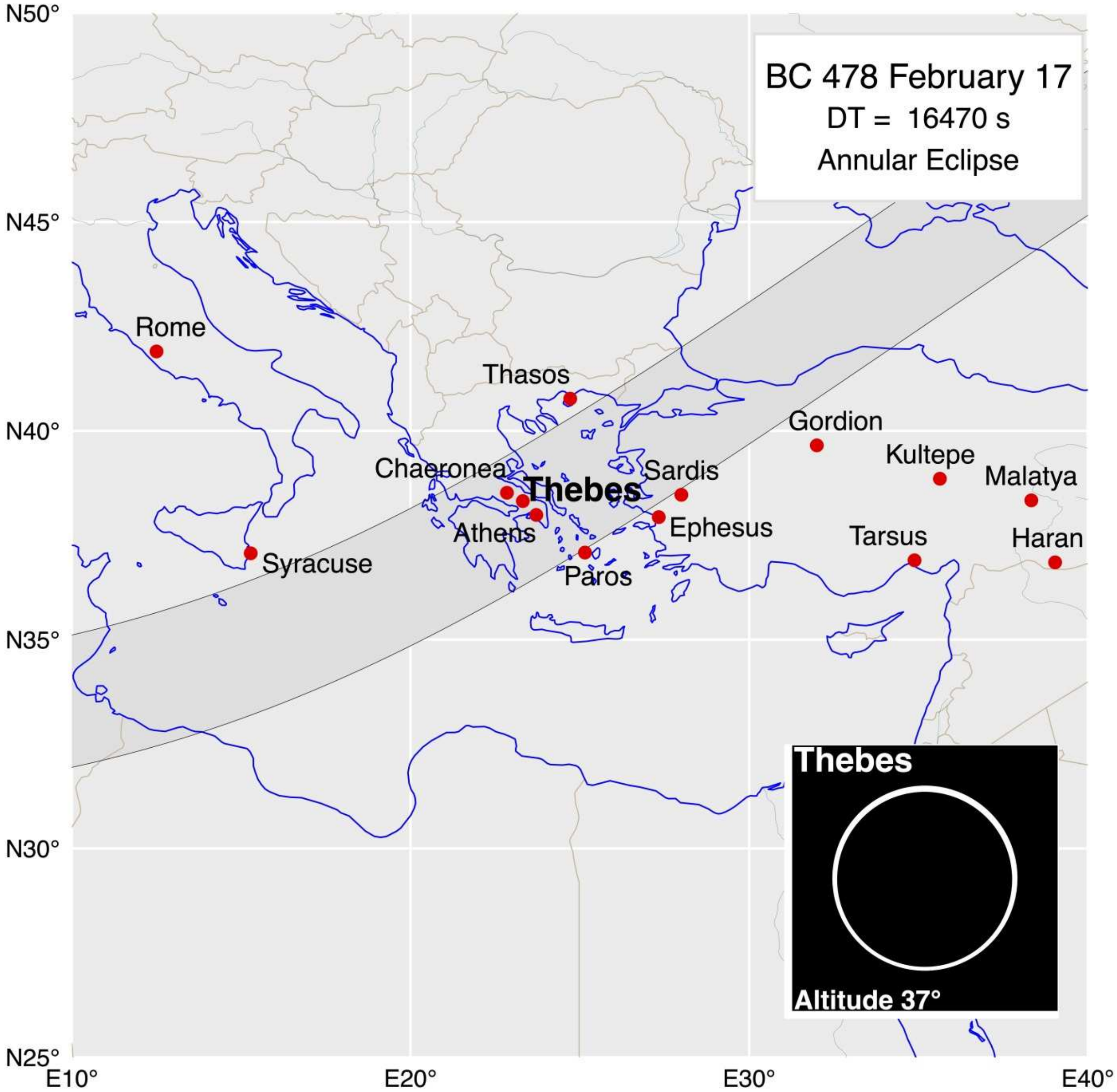

Figure 5: Track of the annular eclipse of BC 478 February 17. The inset shows the annulus of the Sun's disk visible at Thebes at the time of greatest coverage (Catherine Hohenkerk, map outline from Natural Earth).

the belt of totality.

Fotheringham (1920) also adopted the eclipse of BC 463, and concluded that there was a reasonable presumption that the eclipse was total at Thebes. However, he added the rider that the Greek verb for 'reft' is in the present tense, and is consistent with *incomplete* action. His erroneous presumption led to a solution incompatible with the other eclipses in his diagrammatic solution, and he concluded rightly that his presumption of totality at Thebes was not justified.

In summary, a date of BC 463 April 30 for the reference to an eclipse in the poem seems most likely, as this is the eclipse with the greatest degree of obscuration at Thebes during the period of Pindar's odes.

4.4 Thucydides: BC 431 August 3

This eclipse is said by Thucydides (ca. BC 460–400) to have occurred only a few months after the start of the Peloponnesian War between Athens and Sparta in which he was actively involved. The war began towards the end of the year when Pythodorus was archon in Athens, and thus in the spring of BC 431, which agrees with

> During the same summer at the beginning of the lunar month (the only time, it seems, when such an occurrence is possible), the Sun was eclipsed after midday; it assumed the shape of a crescent, and became full again and during the eclipse some stars became visible (Thucydides, II, 28; trans. Livingstone, 1949: 109).

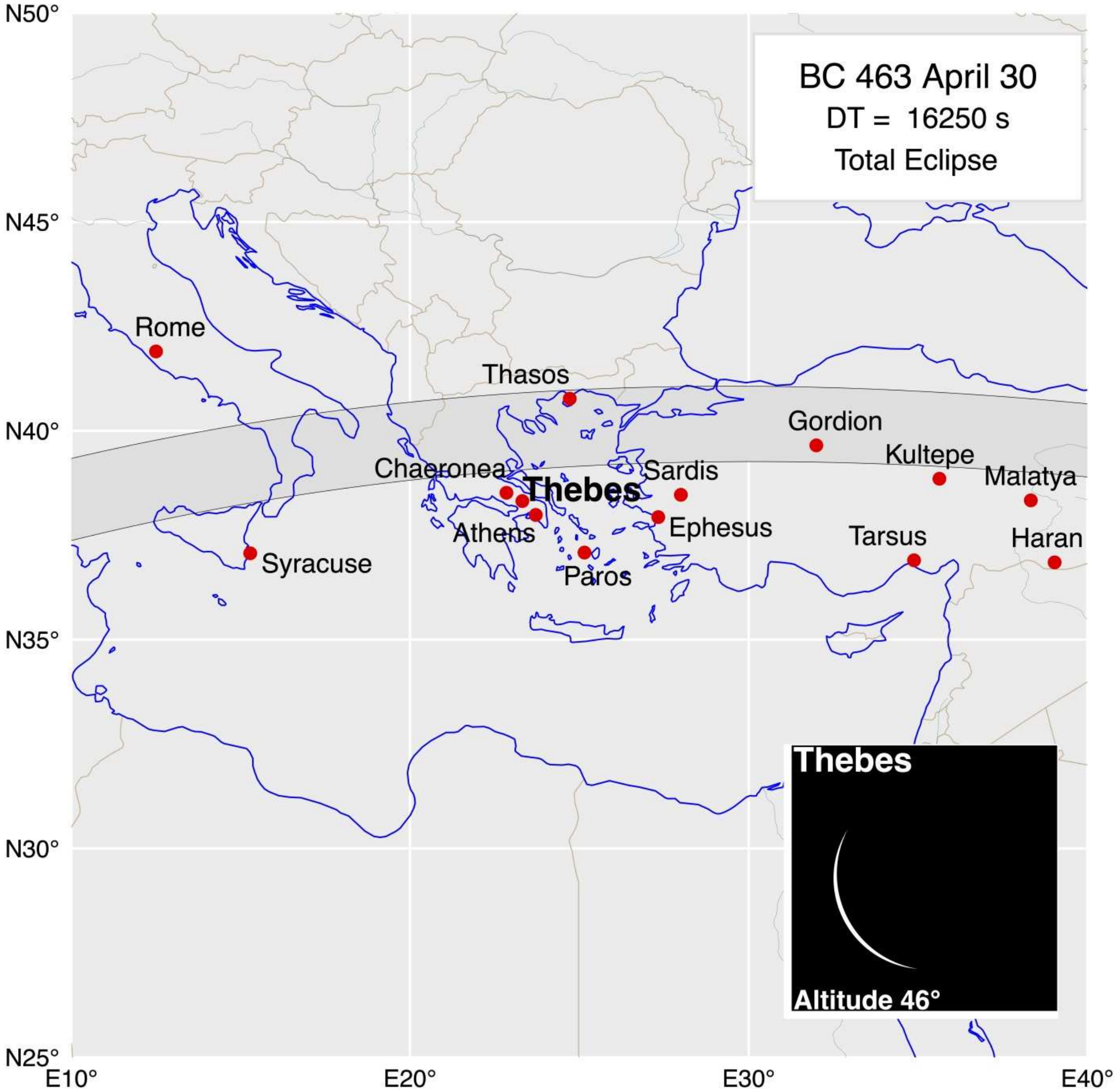

Figure 6: Track of the total eclipse of BC 463 April 30. The inset shows the maximum coverage of the Sun's disk at Thebes (Catherine Hohenkerk, map outline from Natural Earth).

The annular eclipse of BC 431 August 3 agrees with the chronology of the Peloponnesian War. The central track is plotted in Figure 7, with the inset showing the greatest phase at Athens when the Sun was at an altitude of 17°. As seen from mainland Greece, about 12% of the solar diameter remained uncovered, and the Sun would have appeared crescent-shaped from any part of Greece. Therefore, we cannot resolve the question of where exactly in Greece the observation was made.

The maximum phase of the eclipse occurred late in the afternoon at around 5:30 pm local time, about an hour and a half before sunset. The duration from maximum phase till the end of the eclipse was about one hour. Thus, the eclipse ended before sunset as seen from Greece, in agreement with the report. At an altitude of 17° above the horizon, we calculate that atmospheric extinction would have reduced the glare of the crescent by at least 60%, thus making it less blinding to the naked eye and discernible as a crescent. It might also have been seen through thin cloud, a dusty atmosphere, or as fluttering images on the ground between the shadow of leaves under a tree. This pin-hole projection effect is often witnessed during eclipses.

The eclipse is reported as having occurred after midday. We interpret this as a general statement, which does not conflict with the fact that this eclipse occurred late in the afternoon. However, a more serious point of contention in the report is the assertion that "… some stars …"

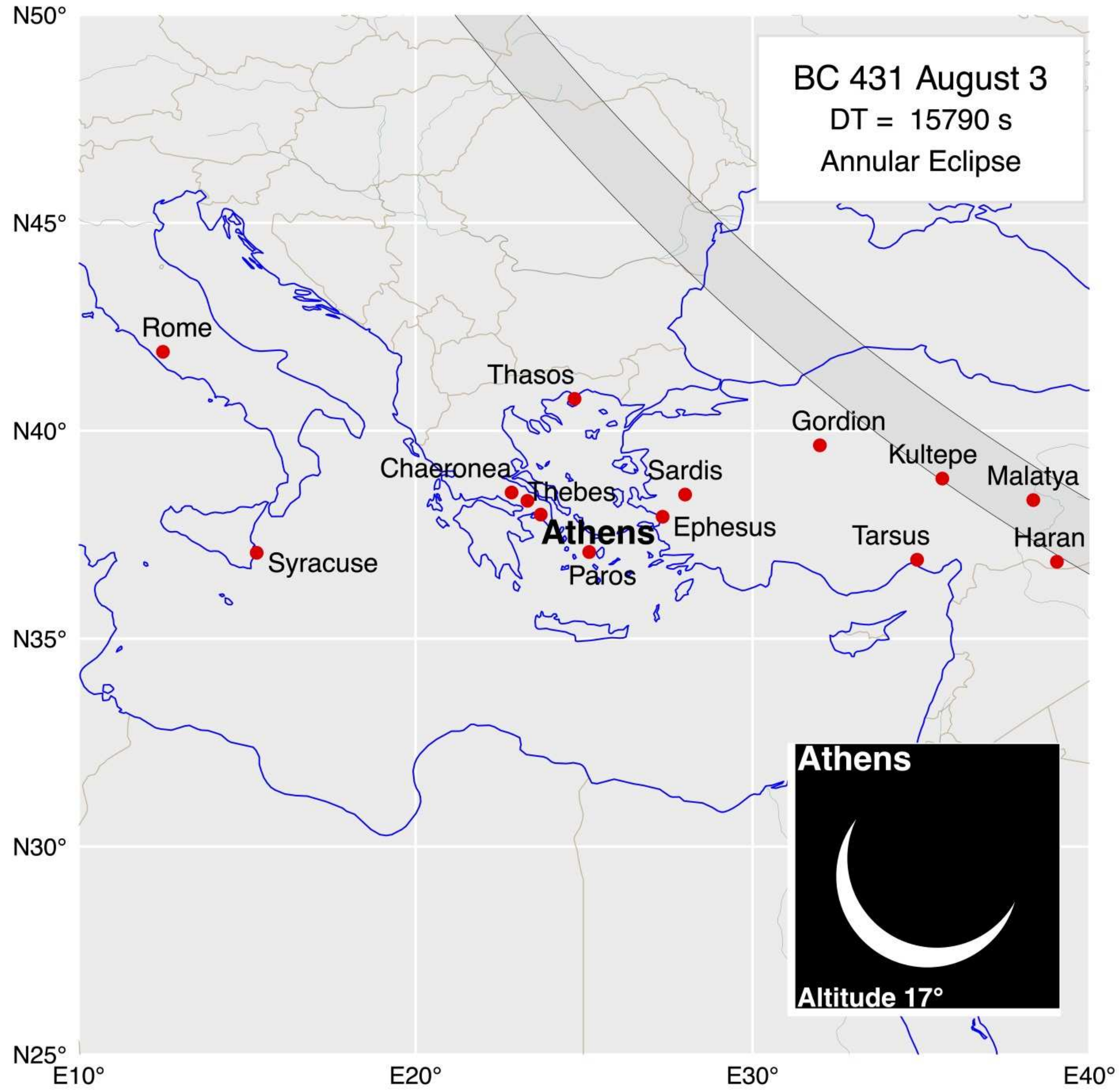

Figure 7: Track of the annular eclipse of BC 431 August 3. The inset shows the crescent of the Sun visible from Athens at the time of maximum eclipse there (Catherine Hohenkerk, map outline from Natural Earth).

were seen. Fotheringham (1920) and Stephenson and Fatoohi (2001) concluded that only Venus was bright enough (magnitude –3.8) to have been seen 20° east of the Sun, and therefore higher in the sky as the Sun moved towards setting in the west. We presume that Thucydides was using some poetic licence.

In conclusion, there is little doubt that Thucydides was alluding to the eclipse of BC 431 August 3.

4.5 Xenophon: BC 394 14 August 14

The historian Xenophon (BC 430–354) in his *Hellenica* (IV: 3, 10) records a solar eclipse in which the Sun appeared like a crescent. This event was observed by King Agesilaus II and his army who were on the way to attack the Theban forces. Xenophon, who travelled with the army of Agesilaus, gave the following account:

> Next day he (Agesilaus) crossed the mountains of Aachaea Phthiotis and for the future continued his march through friendly territories until he reached the confines of Boeotia. Here at the entrance of that territory, the Sun seemed to appear in a crescent shape. (Xenophon, trans. Dakyns, 1892(II): 54).

Two later writers provide additional details. Writing in the first century BC, Diodorus Siculus (*Library of History*, XIV: 82) gave the date as the archonship of Diophantus, the second year of the 96th Olympiad, which is equivalent to BC 395/394. The first-century AD author Plutarch in his *Life of Agesilaus* (XVII.3–XVIII.1), specified the site where the eclipse was seen:

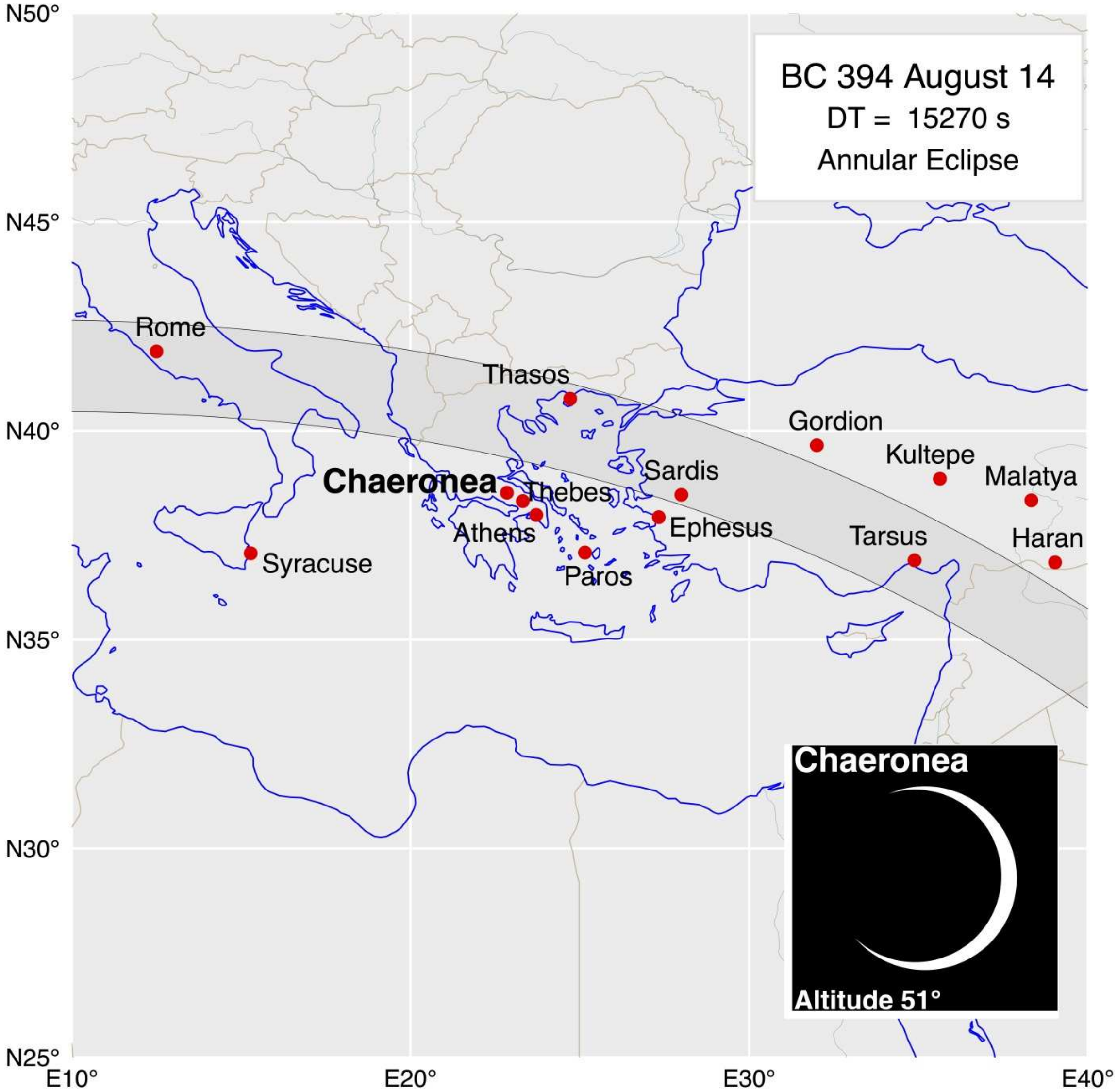

Figure 8: Track of the annular eclipse of BC 394 August 14. The inset shows the crescent of the Sun as seen from Plutarch's hometown of Chaeronea at the time of greatest eclipse there (Catherine Hohenkerk, map outline from Natural Earth).

> Agesilaus now marched through the pass of Thermopylae, traversed Phocis, which was friendly to Sparta, entered Boeotia, and encamped near Chaeronea. Here a partial eclipse of the Sun occurred ... After advancing as far as Coroneia and coming in sight of the enemy ... (Plutarch, *Lives*, trans. Perrin, 1917(V): 47).

It may be deduced that the eclipse was seen near Chaeronea, the hometown of Plutarch. The only significant eclipse visible in that region around BC 395/4 was that of BC 394 August 14 (see Figure 8). This was an annular eclipse in which 3% of the solar disk remained uncovered by the Moon in the central zone. As seen from Chaeronea, 13% of the solar disk was uncovered at greatest phase at about 9:30 am local time. The sky would still have been bright, and, at an altitude of 51°, the crescent Sun would have been too dazzling to look at directly in a clear sky. It might have been seen through thin cloud, a dusty atmosphere, or as images on the ground under a tree, as in our consideration of the previous eclipse in BC 431. Another possibility is that the eclipse occurred when the army was further north, near the belt of central annularity at the pass of Thermopylae. There the crescent would have been much narrower and observable directly in a clear sky. However, this would presuppose that the order of events was not as recorded by Xenopon and Plutarch.

In agreement with Stephenson (1997: 366), we conclude that Xenophon was referring to the eclipse of BC 394 August 14, which was seen near Chaeronea at around 9:30 am local time.

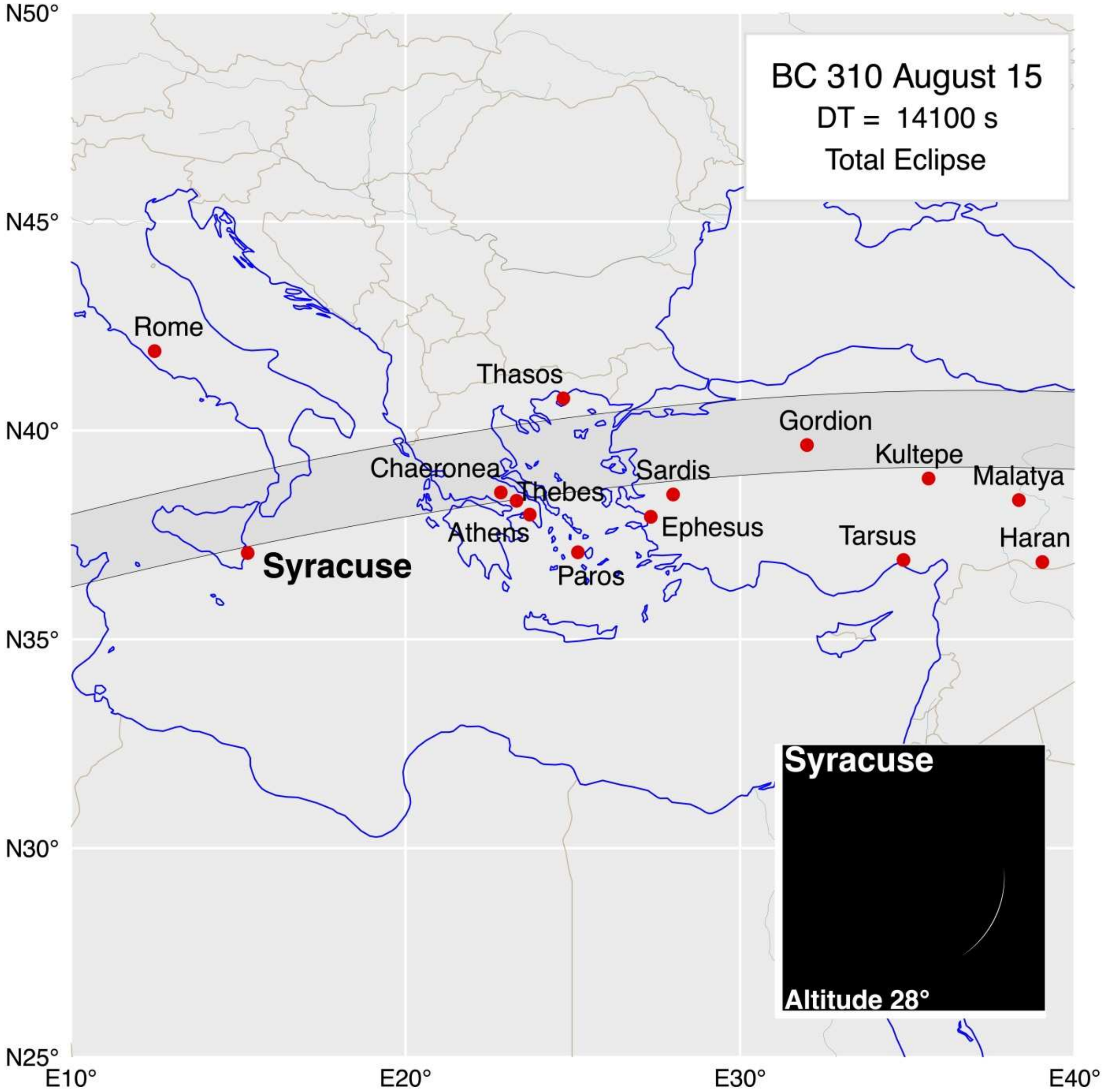

Figure 9: Track of the total eclipse of BC 310 August 15. The inset shows the very thin crescent of the Sun remaining at greatest coverage at Syracuse. If Agathocles had set sail to the north after leaving Syracuse, he would have witnessed a total eclipse (Catherine Hohenkerk, map outline from Natural Earth).

4.6 Agathocles: BC 310 August 15

The first century BC historian Diodorus Siculus (Diodorus of Sicily) records in his *Library of History* (XX: 5–6) that an eclipse, causing darkness by day, was seen by the tyrant Agathocles. At the time, Agathocles with a fleet of 60 ships was escaping from Syracuse harbour, which had been blockaded by the Carthaginians.

Diodorus relates that Agathocles and his fleet escaped from Syracuse one evening after sunset. Diodorus adds:

> On the next day there occurred such an eclipse of the Sun that utter darkness set in and the stars were seen everywhere (trans.Geer, 1954: 155–157).

Diodorus states that the event occurred during the archonship of Hieromemnon of Athens. From the list of Athenian archons given by Bickerman (1980:139), the year of the archonship of Hieromemnon corresponds to BC 310/309. The only large eclipse visible in Sicily near this date is that of BC 310 August 15. It was very nearly total at Syracuse (see Figure 9).

After Agathocles and his fleet escaped from Syracuse, they eventually reached Libya six days later. It is not known from the account whether the fleet of Agathocles sailed to the north or south of Syracuse after the escape. As shown in Figure 9, we compute that the path of totality passed a little to the north of Syracuse. Only in region north of Syracuse would "… utter darkness set in …" during the eclipse, with many stars visible. Our computations thus provide definitive evidence that on escaping from Syracuse harbour, Agathocles' fleet sailed northwards. Fotheringham (1920) presumed that the fleet could have been anywhere along the eastern seaboard of Sicily, thus not ruling out the possibility that the fleet sailed south from Syracuse.

In brief, not only is the year of the eclipse correctly specified by Diodorus, but he is also accurate in his description of the total eclipse.

4.7 Plutarch: AD 71 March 20

Plutarch (ca. AD 46 –120) gives an account of a total eclipse in his dialogue entitled *The Face on the Moon* (931D-E):

> Now grant me that nothing that happens to the Sun is so like its setting as a solar eclipse. You will if you call to mind this conjunction recently which, beginning just after noon it made many stars shine out from many parts of the sky and tempered the air in the manner of twilight. (trans. Cherniss and Helmbold, 1957(XII): 117–119).

This is the oldest known—and one of the few preserved early accounts—of a solar eclipse that mentions a fall in air temperature.

Plutarch adds in section 932E of *The Face on the Moon*:

> Even if the Moon, however, does sometimes cover the Sun entirely, the eclipse does not have duration or extension; but a kind of light is visible about the rim which keeps the shadow from being profound and absolute; (trans. Cherniss and Helmbold, 1957: 121).

The beginning of the dialogue is lost, together with the date and place of the eclipse. Plutarch's dialogues are usually set in places in Greece, but sometimes in Rome. He mentions "… this recent conjunction …", and this indicates that the eclipse was a contemporary event that occurred in his lifetime. He was born in Chaeronea, where he was resident until his appointment in ca. AD 95 as a priest in Delphi. He travelled throughout Greece and visited Rome at least twice.

Only the eclipses of AD 71 March 20 (Figure 10) and AD 75 January 5 (Figure 11) were total or nearly total in the region of interest during his lifetime. Stephenson and Fatoohi (1998) analysed these in detail, and eliminated AD 75 as a contender because it occurred after 4 pm local time in Greece, and this is at variance with his statement "… beginning just after noon." Also, Figure 11 shows that the path of totality passed to the north of Greece, and in southern Greece in the region of Athens at least 16% of the Sun's disk remained uncovered. The brightness of the sky would have been too great for stars to be seen.

Using our latest ΔT solution from Morrison et al. (2020), we calculate that the eclipse of AD 71 March 20 was almost total at Athens (see Figure 10). This agrees with the fact that the report mentions that stars were seen, because this means that the observer was in, or very near the path of totality. Calculation shows that AD 71 March 20 was a hybrid eclipse: that is, the apparent diameter of the Moon was almost identical to that of the Sun, and varied from being annular to total along the track. At greatest phase in Greece the eclipse was total, as distinct from annular, and the brilliant photosphere of the Sun would have been completely hidden during totality, allowing the inner part of the relatively faint corona to be seen as a dull glow around the Moon, just as described by Plutarch. Furthermore, the duration of totality would have been very short (several seconds), in agreement with Plutarch's comment that the eclipse "… did not have duration or extension."

One point against the identification of Plutarch's report with the eclipse of AD 71 March 20 is that he says it started after noon, whereas, computation shows that totality occurred close to 11 am in Greece. This discrepancy may be due to the vagueness in the observers' definition of 'noon'. We compute that between 11 am and noon the solar altitude increased by less than 3°. Hence, as the recorded timing of the eclipse appears rather informal, the error of about an hour is probably not very significant. The observers seem to have been more concerned to note that "… many stars …" shone out and that there was a noticeable drop in temperature.

We cannot be absolutely certain where in Greece the eclipse was witnessed. Figure 10 shows our best estimate of the position of the track passing over Athens. However, the uncertainty in the value of ΔT is such that the track could have been positioned further west, perhaps passing over Chaeronea, where Plutarch was resident. Chaeronea is about 75 arc minutes of longitude west of the track plotted in Figure 11, and if the track passed over there, the value of ΔT would need to be about 300s less than the value in our computations; i.e. 9500s. This is close to the lower range of our values of ΔT (9440 to 9830s) for totality somewhere in Greece (Stephenson et al., 2016). This is less likely than values towards the upper end of the range because of the constraints on ΔT imposed by other eclipse results around this epoch (see Morrison et al., 2020).

From our consideration of the physical appearance of the eclipse and our latest results for the rotation of the Earth, we conclude that the eclipse was total somewhere in a corridor lying between Delphi in the west and Athens in the

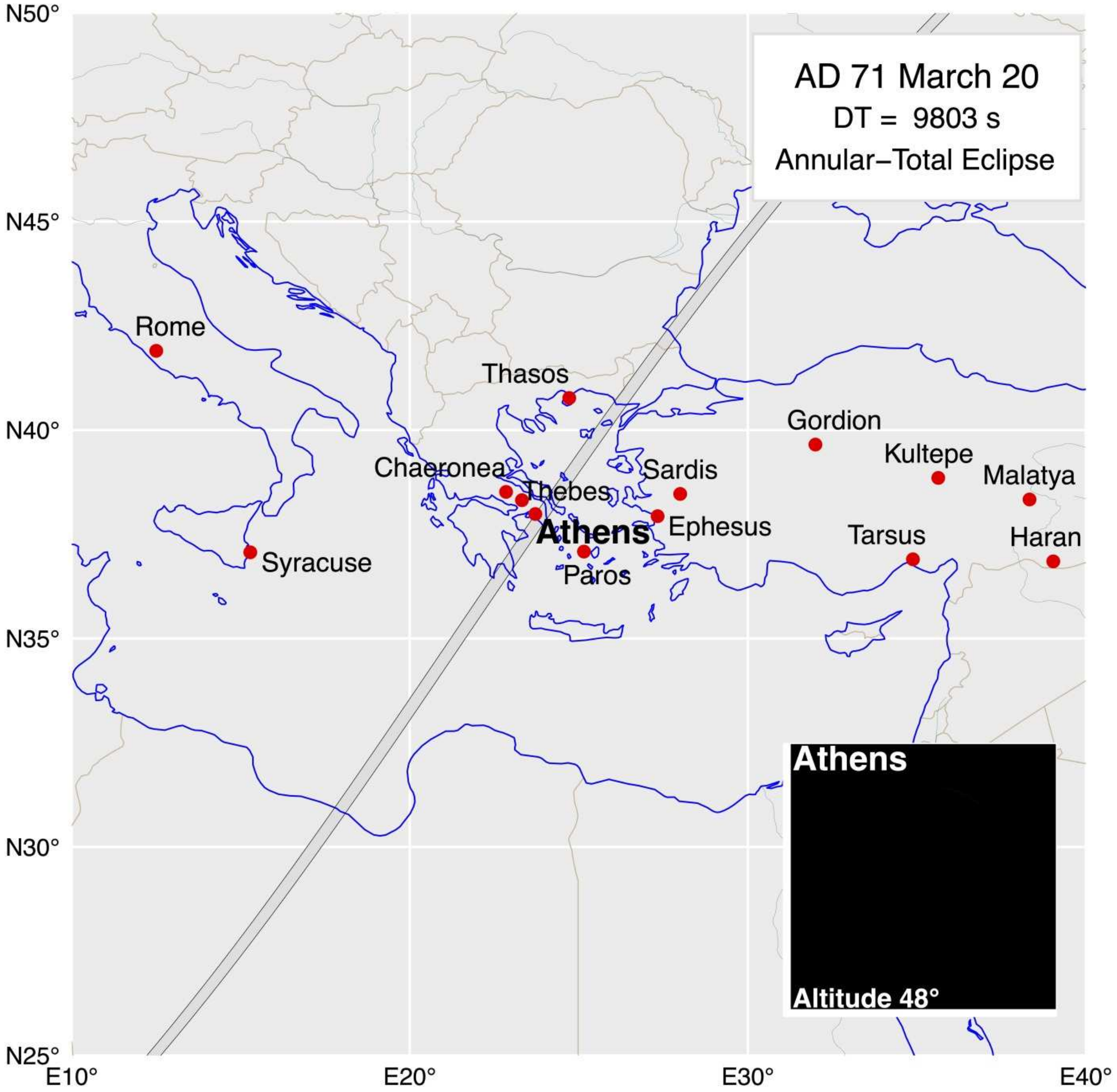

Figure 10: Computed track of the annular-total eclipse of AD 71 March 20 with the time correction ∆T equal to +9803s. Athens is very close to the edge of the track. A possible reduction by 300s in DT would move the computed track westwards, such that it passed over Chaeronea (Catherine Hohenkerk, map outline from Natural Earth).

east. After a careful consideration of the geographical locations of Plutarch's family and friends, Fotheringham (1920: 112–114) concluded that the eclipse was total either at Chaeronea or 19 miles to the west, at Delphi. This presumption led to one of the tightest constraints in his diagrammatic solution for the secular accelerations of the Sun and Moon.

5 CONCLUSIONS

Our consideration of the precise tracks of the eclipses and their physical descriptions in the historic reports adds considerable weight to the dates accepted by most historians today. We summarise our conclusions here:

(1) Archilochus: BC 648 April – highly likely; observed from Thasos, or perhaps Paros (Figure 1).
(2) Herodotus: BC 585 May 28 – definite; the battle took place in Asia Minor in the corridor defined by the total eclipse (Figure 3).
(3) Pindar: BC 463 April 30 – very likely; observed from Thebes, or possibly just to the north of Thebes (Figure 6).
(4) Thucydides: BC 431 August 3 – definite; could have been observed from Athens, but anywhere in Greece is possible (Figure 7).
(5) Xenophon: BC 394 August 13 – definite; observed near Chaeronea around 9:30 am local time (Figure 8).
(6) Agathocles: BC 310 August 15 – definite; sailed north on leaving Syracuse (Figure 9).

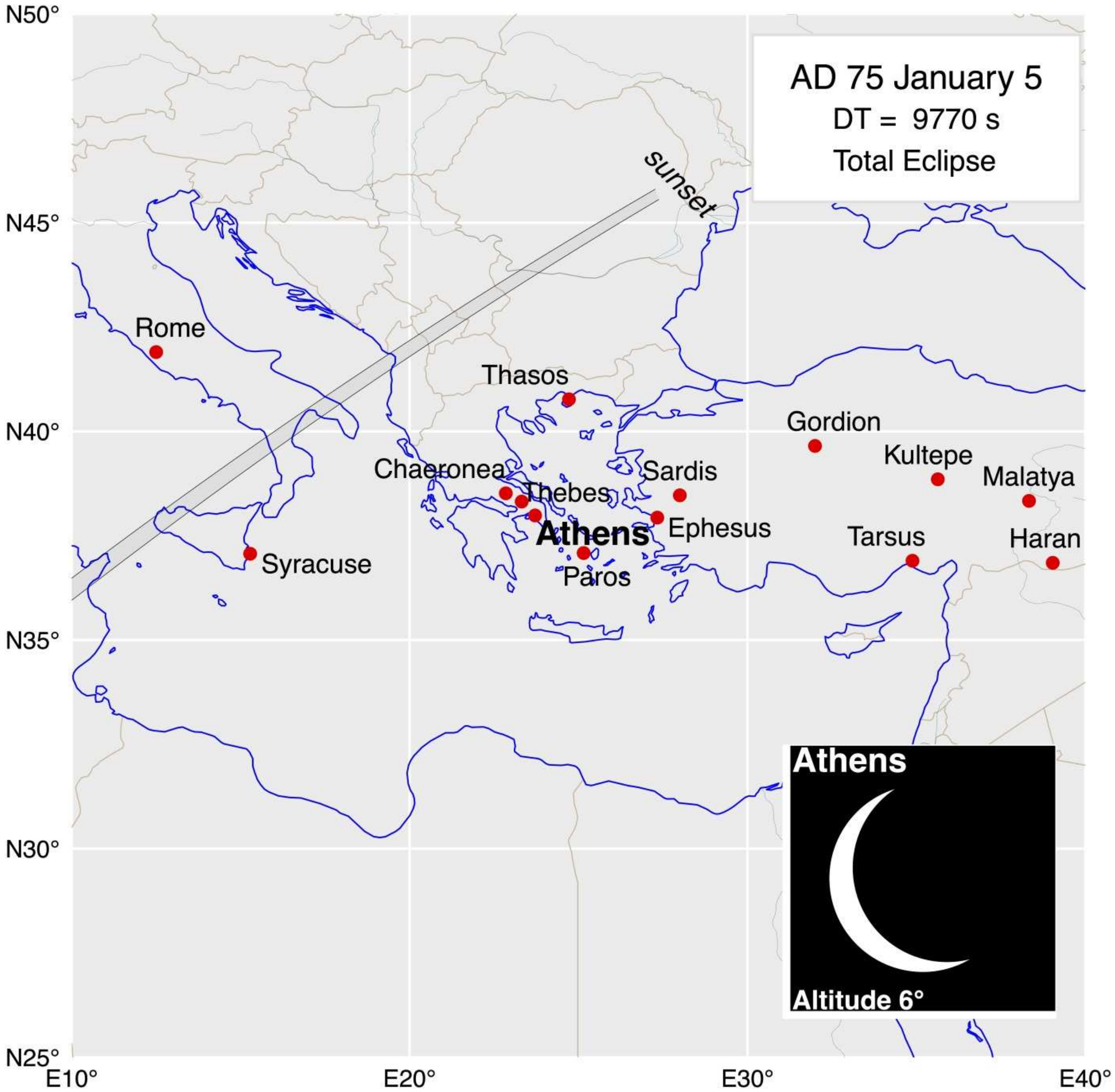

Figure 11: Track of the total eclipse of AD 75 January 5. The inset shows the crescent of the Sun's disk remaining at the greatest coverage as seen in Athens, about half an hour before sunset (Catherine Hohenkerk, map outline from Natural Earth).

(7) Plutarch: AD 71 March 20 – definite; observed somewhere in Greece between Athens and Delphi (Figure 10).

6 ACKNOWLEDGEMENTS

We thank the referees for their suggestions which have improved the presentation of this paper. The authors acknowledge HM Nautical Almanac Office and the International Astronomical Union's Standards of Fundamental Astronomy.

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In the field of Earth's rotation he analysed timings of lunar occultations in the period AD 1600 to 1955 in order to derive decade fluctuations in the Earth's rate of rotation. In 1975 he derived an accurate value for the tidal acceleration of the Moon, which was later corroborated by Lunar Laser Ranging to the corner-cube reflectors on the Moon. This value for the tidal acceleration of the Moon was adopted in his long collaboration with F. Richard Stephenson in the analyses of historical records of pre-telescopic solar and lunar eclipses. This led to a series of papers on the historical fluctuations on decade and centennial time-scales in the Earth's rate of rotation. Notable amongst these is the series of three papers in 1984, 1995 and 2016 (with Catherine Hohenkerk) in the *Philosophical Transactions of the Royal Soc*iety. He continues to work in this field.

Catherine Y. Hohenkerk started working at the Royal Greenwich Observatory straight from school in 1971. She obtained an HNC in Mathematics, Statistics and Computing, followed by a BSc (Hons.) in Mathematics, both by day release. She worked in the Solar and Computer Departments before being transferred to HM Almanac Office in 1978, where she remained, despite the closure of the Observatory and the relocation to Rutherford Appleton Laboratory in 1998, and then to the UK Hydrographic Office in 2006, until retirement at the end of January 2017. During her career she has been involved with the content, programming and production of all the almanacs. In 2005 she received the US Naval Observatory Superintendent's Award.

Catherine was elected a Fellow of the Royal Institute of Navigation and of the Royal Astronomical Society. She is a member of the International Astronomical Union, its Division A, Fundamental Astronomy, and has been President of Commissions 4, Ephemerides (2012–2015), and A3 Fundamental Standards (2015–2018), and is Chair of the standing Working Group Standard of Fundamental Astronomy (SOFA), which provides software that support IAU Resolutions.

She collaborated with Richard Stephenson and Leslie Morrison on the paper "Measurement of the Earth's rotation: 720 BC to AD 2015, which was published in *Philosophical Transactions of the Royal Society* in 2016. Recently she and Ken Seidelmann edited a book titled *The History of Celestial Navigation: Rise of the Royal Observatory and Nautical Almanacs*, which will be published by Springer in their Historical and Cultural Astronomy Series.

Editorial Comment: We regret that the quality of the figures in this paper is not up to the desired standard. Unfortunately, we encountered 'production difficulties' when we converted the Word files (which were acceptable) to pdf files. Rather than delay publication further, the authors of this paper and the *JAHH* Editorial team decided to publish the paper 'as is'. Those who want better-quality images can email me (wayne.orchiston@gmail.com) and I will send you a Word version of the paper.