3
The Front Dial and Parapegma Inscriptions

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Y. Bitsakis

Department of Primary Education, National and Kapodistrian University of Athens/ Institute of Historical Research/National Hellenic Research Foundation, Greece
E-mail: bitsakis@gmail.com

A. Jones

Institute for the Study of the Ancient World, New York, USA
E-mail: alexander.jones@nyu.edu

Abstract

The dial at the center of the front face of the Antikythera Mechanism was surrounded by two scales, one representing the zodiac, the other the Egyptian calendar year. The Zodiac Scale was inscribed with the names of the zodiacal signs as well as series of index letters in alphabetic order, while the Egyptian Calendar Scale was inscribed with the Greek names of the Egyptian months. In addition, two rectangular plates, the remains of which survived displaced from their original positions, bore an inscription, called the Parapegma Inscription, comprising an alphabetically indexed list of annually repeating astronomical events relating to the Sun and to fixed stars. This paper gives transcriptions and translations of the inscriptions on the dial scales and the Parapegma Inscription, and deduces the original structure, layout, and location of the Parapegma Inscription. A provisional astronomical analysis of the data in the Parapegma Inscription and tentative restorations of some of its damaged and missing lines are also provided.

3.1 Introduction

The front face of the Antikythera Mechanism bore a single circular dial that occupied most of the area of a square plate, the Dial Plate (Fig. 3.1). The dial had multiple pointers radiating from its center to represent the longitudes of the Sun, Moon, and the five planets known in Antiquity.[1] Surrounding the dial were two concentric graduated scale rings. The outer Egyptian Calendar Scale was divided into twelve sectors, each containing thirty subdivisions, and one smaller sector containing five subdivisions, representing the 365 days of the Egyptian calendar year. Each sector was inscribed with the Greek name of an Egyptian month, running clockwise. The inner Zodiac Scale was divided into twelve sectors, each containing thirty subdivisions, representing the twelve zodiacal signs and the 360 degrees of the zodiac.[2] Each sector of the Zodiac Scale was inscribed with the name of a zodiacal sign, running clockwise in order of increasing longitude, and with small letters, running clockwise in alphabetic order, placed outside and immediately clockwise of the graduation marks corresponding to various degrees in the zodiacal signs. These "index letters" linked the associated degrees to lines of an inscription, called the Parapegma Inscription, that was inscribed on two rectagular Parapegma Plates, which we name PP1 and PP2.

1 Paper 5 in this series - IAM 5.5; Freeth & Jones 2012, section 2.3; previously conjectured by Wright 2002.

2 The sectors of the Zodiac Scale are not exactly equal, as shown by Evans, Carman, & Thorndike 2010, who argue that this was an intentional feature making it possible to display the Sun's true longitude with the same pointer that indicated the Egyptian calendar date. Other reconstructions since Wright 2002b have hypothesized separate pointers for the true Sun and mean Sun (though Wright presciently remarked that this was necessary "on the assumption that both Zodiac and calendar rings were equally divided").

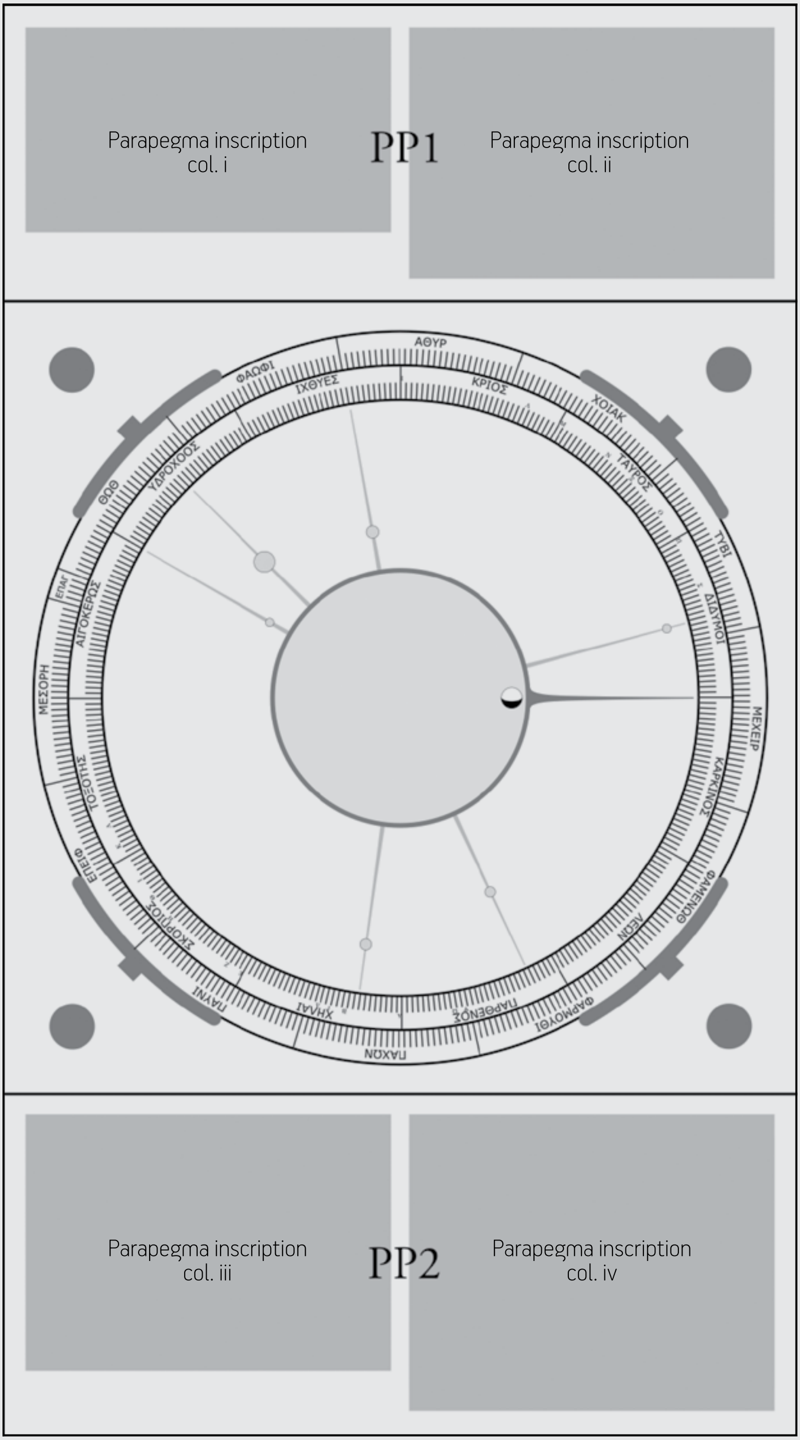

Figure 3.1: *Reconstruction of the Antikythera Mechanism's front face*

The Parapegma Inscription comprised a list of solstices, equinoxes, entries of the Sun into the zodiacal signs, and first and last appearances of stars and constellations before dawn and after dusk. Thus whenever the pointer on the front dial representing the position of the Sun in the zodiac pointed at a degree division bearing an index letter, the viewer could look up the corresponding line of the Parapegma Inscription and read off a prediction of a solar or stellar event predicted for the date in question. We will show in this paper that the Parapegma Plates also formed part of the Mechanism's front face, above and below the Dial Plate, as originally proposed by Price, so that it would have been easy to consult the inscription while watching the dial.[3]

The present edition of the Front Dial Inscriptions and Parapegma Inscription takes advantage of the Polynomial Texture Mapping (PTM) and Microfocus X-Ray Computed Tomography (CT) imaging of the fragments that was carried out in 2005 by the Antikythera Mechanism Research Project in collaboration with the National Archeological Museum.[4] CT has made it possible to read text hidden beneath layers of accreted matter or on surfaces embedded within fragments, for example on portions of the dial scales that are concealed behind PP1 (Fig. 3.2). CT and PTM imaging are both helpful in detecting and reading text on exposed but damaged surfaces. The part of the Parapegma Inscription that we reconstruct as PP1 col. i was entirely unknown to its previous transcribers, Rehm, Price and Stamires. The fragments of plate bearing the text that we assign to the two columns of PP2 were known to Price and Stamires, but many letters that were either invisible or illegible to them can now be read accurately through CT. Even PP1 col. ii, which is on a fully exposed plate, has been augmented with letters that were missed by all previous transcribers from Rehm onwards. Complementing the new imaging technologies, a 1905 photograph has enabled us to locate two of the small fragments as pieces broken off PP2 and to verify the reading of a lost part of PP1 col. ii, for which we were previously dependent on Price's adaptation of Rehm's unpublished transcriptions.

3 Price 1974, 16-17 with Fig. 7.

4 IAM 1.2.

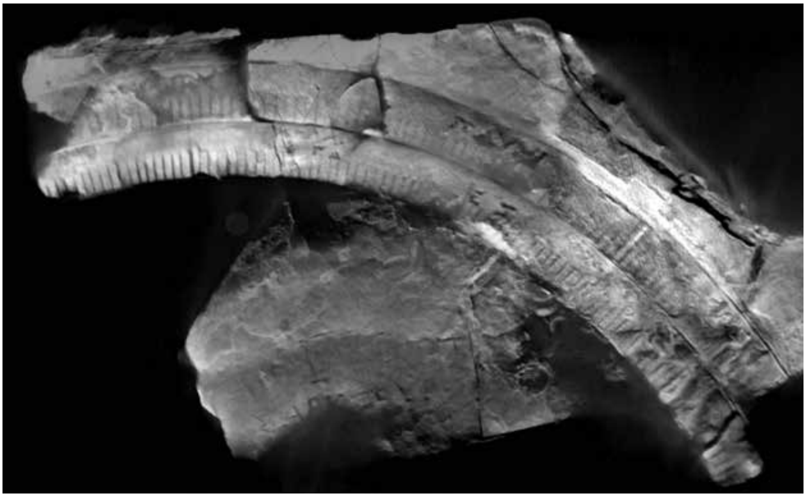

Figure 3.2: *Fragment C, CT composite image of the inscriptions of the Zodiac Scale and Egyptian Calendar Scale*
(*Image: Antikythera Mechanism Research Project)*

With more of the Parapegma Inscription at our disposal, we have learned a great deal about its structure. Rehm and Price recognized that the inscription contains chronologically ordered statements of the first and last morning and evening appearances of certain stars and constellations. It also turns out to contain statements of the solstices and equinoxes and of the Sun's entry into the twelve thirty-degree zodiacal signs. The number of listed events was 42, nearly twice as many as the 24 that Price had guessed. Price's conjecture that the inscription occupied two plates above and below the dial, in columns of text occupying half the width of each plate, was correct, as can be shown both from the logic of the inscription's arrangement and from physical evidence, although his hypothetical placements of the surviving fragments were not.[5] Each of the four columns of the inscription comprised the events falling within one of the four astronomical seasons demarcated by the solstices and equinoxes, and its location on the plates positioned it nearest to the corresponding quadrant of the dial. We have also confirmed another of Price's conjectures, that the dial was oriented such that the graduation marking the beginning of the zodiacal sign Aries and the vernal equinox was at the top. We thus obtain a clearer and more secure reconstruction of the appearance of the Mechanism's front face than has previously been possible.

5 See Price 1974, 17, fig. 7, for his hypothetical layout, according to which the parapegma began in the right half of the upper plate, and continued through two columns on the lower plate, so that the text on C-1, our PP1 col. ii, is the *left* column of his lower plate.

3.2 Fragments preserving parts of the Front Dial and Parapegma Inscriptions

The preserved Front Dial Inscriptions are entirely in Fragment C, while parts of the Parapegma Inscription are in C and the four small fragments 9, 20, 22, and 28.

The dimensions of Fragment C (Fig. S3 and S4) are approximately 106 mm (width) by 96 mm (height) by 22 mm (thickness). It consists of three originally separate major components that fused together during the long immersion of the Mechanism. These are, listed from back (C-2) to front (C-1):

(1) The Moon Casing, a circular disk or boss of diameter 65 mm having a shallow cylindrical wall (1 mm thickness) projecting outwards 7 mm from the disc where not broken away, the whole resembling the lid of a jar. There are numerous mechanical details that need not be described here.[6] This was the casing, with a surviving fragment of the assembly, of a display of the spherical Moon making its revolution around the Earth while exhibiting its cycle of phases. We are not concerned with the Moon Casing in the present paper.

(2) Part of the front face of the Mechanism, the principal element of which was the Dial Plate, a nearly square plate approximately 165 mm height by 171 mm width, with a circular cutout of diameter approximately 132 mm, and a ring-shaped sink, about half the depth of the plate, having outer diameter about 162 mm and inner diameter about 146 mm. One corner of the Dial Plate, amounting to a little less than a quarter of the whole, survives.

The ring-shaped surface between the inner circumference of the sink and the circumference of the cutout was engraved with the Zodiac Scale. This scale, about a fifth of which survives, was graduated by radial lines into twelve sectors labelled with the names of the signs of the zodiac (letter height averaging about 1.8 mm), and each sector was subdivided by shorter radial lines (about 3 mm long) into 30 individual degrees, some of them labelled with letters of the Greek alphabet (letter height averaging about 1.2 mm).[7] The sink, which was normally concealed, was drilled through with 365 small holes, of diameter about 0.7-0.8

6 For details see Wright 2006, where the purpose of this component was brilliantly explained for the first time, and Carman & Di Cocco 2016.

7 A shallow circular groove runs around the dial along the exterior ends of the short graduation strokes on both the Zodiac and Egyptian Calendar Scales. Perhaps these were guidelines to help the engraver keep the strokes equal in length.

mm, at approximately equal spacing around the ring.[8]

The sink was occupied by a removable ring, the Egyptian Calendar Ring, whose thickness was approximately equal to the sink's depth so that its exposed front face was flush with the Dial Plate. This face was engraved with the Egyptian Calendar Scale, graduated into sectors corresponding to the twelve 30-day months and the five additional "epagomenal" days of the Egyptian calendar year, with smaller graduations marking the single days; again about a fifth of this scale survives. The Greek names of the Egyptian months were inscribed in the pertinent sectors (letter height averaging about 1.8 mm). Somewhere on the back face of the ring there must have once existed a peg placed so that it could be fitted in any of the 365 holes in the zodiac ring, allowing any desired alignment of the Egyptian year with the zodiacal signs.[9] It was thus a moveable calendar ring for the "wandering" year of the Egyptian calendar. The exposed front faces of the Dial Plate, the Egyptian Calendar Ring, and the Zodiac Ring were all more or less flush.

The surviving corner of the Dial Plate is perforated by a small rectangular hole, though which passes a cylindrical shaft joining a circular thumb button on the Dial Plate's front to a flat bolt on the back (Fig. 3.3). The bolt ran through a bearing riveted to the plate's back along its edge (only one supporting block of the bearing flanking the bolt survives), so that by means of the thumb button it could be slid back and forth a few millimeters. With the button at its furthest position from the plate's edge, the bolt's end would be approximately flush with the edge. This was evidently a catch by which the Dial Plate could be held in position or removed to expose the gearwork behind; there were probably such catches in all four corners of the plate.[10]

8 The outer circumference of the sink appears to be cut right through the Dial Plate so that the part comprising the sink and the Zodiac Scale constitutes a separate element from the outer part of the Dial Plate. This may have been a consequence of imperfect workmanship in making the sink (M. T. Wright, by personal communication). The parts of the plate were held together by a thin backing ring and a curious channel-shaped feature that ran along the back of the scales. There are also remains of what may have been a second, smaller backing ring adhering to the back of the zodiac scale, suggesting that there once existed a further plate element filling in the circular cutout and providing a “background” for the revolving pointers.

9 If there had been more than one peg, irregularities in the positions of the pegholes might have made it difficult to install the ring in some orientations.

10 Wright 2011, 12. In Fragment F there is a broken corner of a plate furnished with a very similar sliding catch. The catch is in better condition than the one in C, and the bearing is intact. The identification of this corner as part of the Back Cover Plate (Freeth & Jones

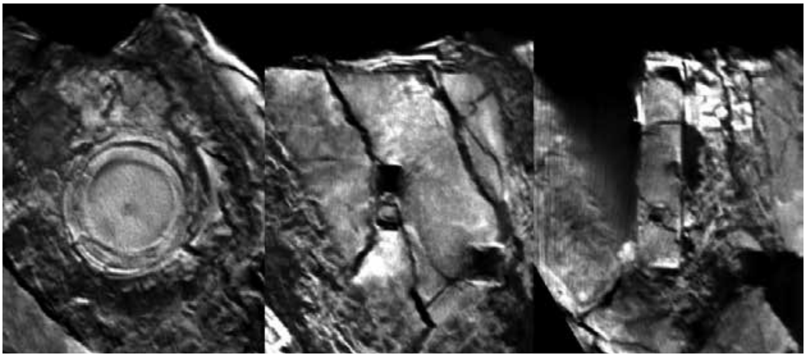

Figure 3.3: *Fragment C, CT slices through the thumb button (left), hole in Dial Plate (center), and bolt of the sliding catch (right, with remains of the mounting of the bearing to the bolt's right, near the upper edge)*
(Images: Antikythera Mechanism Research Project)

The original orientation of the surviving part of the Dial Plate, relative to the Mechanism as a whole, is partially determined by the two surviving straight edges of the plate, which are respectively perpendicular and parallel to a radius running from the center point of the scales through the graduation on the Zodiac Scale marking the beginning of the zodiacal sign Libra. The names and letters inscribed on the dials do not establish which of the four possible orientations is correct, since they run around the rings, perpendicular to whatever radius passes through them.[11]

(3) The Parapegma Plates, two plates inscribed with text on one face. Both are fragments broken on most sides, so that their original extent is not immediately obvious, but one of them has part of a straight lower edge, and the other has part of a straight upper edge preserved. These edges are exactly parallel to the lines of inscribed text. The larger fragment, which we will call PP1, is pressed against parts of the Moon Casing and the Dial Plate and its scales, and it is significantly buckled, especially where it lies on top of the thumb button. Its inscribed text faces forwards, and is oriented such that the beginning of Libra on the Zodiac Scale is upward. Its lower edge is preserved.

2012, 1.4.1) is not at all a certainty since the fragment is uninscribed and is stuck on F with the face bearing the thumb button facing inwards, against the Back Plate, so its position has obviously been disturbed. The possibility that it was actually another corner of the front Dial Plate that broke off and fell through to the rear of the Mechanism cannot be excluded.

11 Decisive physical evidence, such as matching fracture marks, seems to be lacking that would demonstrate whether (and if so, in what way) Fragment C was originally joined directly to Fragment A. Price (1974, 12 and 47) believed that he had confirmed such a fit in 1961, but his claim has been contradicted by Wright 2006, 323.

Riveted to the back of PP1 and along the right surviving end of this edge is a bearing (Fig. 3.4) that appears to have been like the less well preserved bearing of the catch on the Dial Plate. There is no evidence of any component mounted on PP1 that would have passed through this bearing. The other fragment, PP2, is pressed against the Moon Casing, and its inscribed side faces backwards (and thus is partly concealed by the Moon Case), again oriented so that the beginning of Libra is upward. Near the left extremity of its straight edge (with respect to the inscribed side), and very close to the edge itself, the plate is perforated by a small drilled hole, apparently filled by a nail or rivet that continues through a thin vestige of a more or less rectangular feature that was mounted on the back (uninscribed) face of the plate (Fig. 3.5).

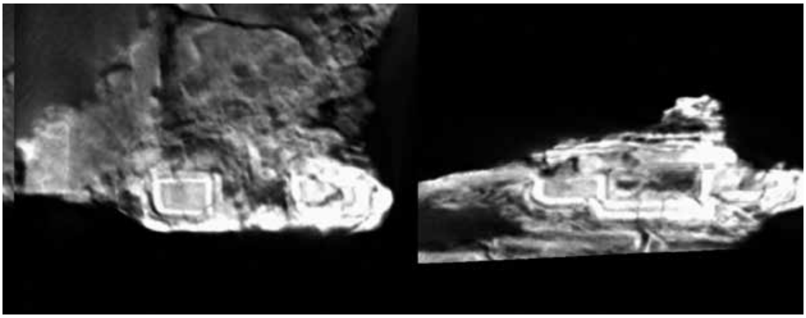

Figure 3.4: *CT slices through the bearing on PP1 in Fragment C: (left) parallel to the plate and through the feet of the bearing; (right) perpendicular to the plate (Images: Antikythera Mechanism Research Project)*

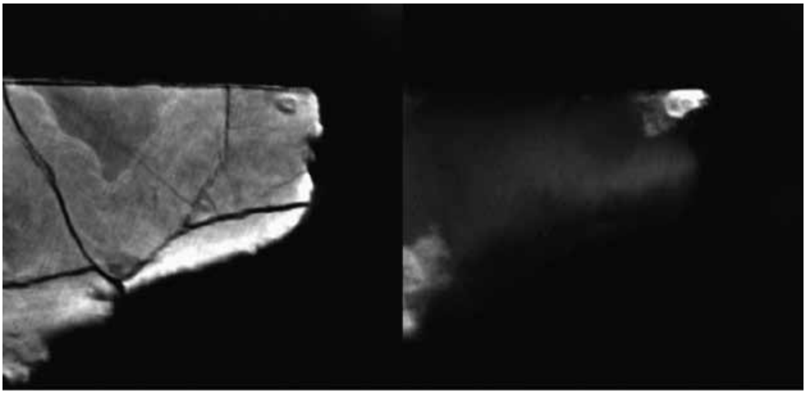

Figure 3.5: *Nail or rivet near the edge of PP2 in Fragment C: (left) CT slice through the plate; (right) CT slice slightly behind the rear (uninscribed) face of the plate (Images: Antikythera Mechanism Research Project)*

In PP1, parts of nine lines of a column of the Parapegma are preserved, with a baseline-to-baseline spacing of about 5.1 mm, along with a vestige of a single line of another column. PP2 preserves parts of four lines of a column of the inscription, with baseline-to-baseline spacing about 5.6 mm. The normal letter height on both plates ranges from about 2.5 mm to about 3.0 mm. The average letter spacing (from left side to left side) is about 3.0 mm, again with considerable variation from line to line.

Later in this paper (section 3.9) we will show, as Price suspected, that the radius through the beginning of Aries on the Zodiac Dial Scale pointed straight upwards, and the radius through the beginning of Libra straight down. This is not, however, something that one can deduce by simply looking at the fragment. As it is normally portrayed in photographs and drawings, and as it has been mounted in the Museum for many years, the radius through the beginning of Libra points upwards, because with this orientation all the inscribed texts visible on the dials and plates are more or less right way up.

The three components of Fragment C described above are stuck together in a manner that obviously does not reflect their original positions in the original Mechanism. Besides facing in opposite directions, the texts inscribed on the two parapegma plates are not exactly horizontal, as defined by the radii perpendicular to the radius through the beginning of Libra. PP1 is tilted about 6° counterclockwise from horizontal, and PP2 is tilted clockwise about 4°. The Moon Casing was originally at the center of the dials, with its periphery concentric with them; but in its present position it is displaced so far off center that part of it is directly behind, and stuck to, the back of the dial scales. All these elements must have shifted in position and orientation during or after the shipwreck.

Photographs allow us to trace the history of Fragment C in reverse order from its present state, which has not significantly altered since 1953.[12] For Fragment C in its previous state, the most substantial evidence we have is the pair of Karo's 1905 photographs showing C-1 (supplementary Fig. S10) and C-2, and the 1918 photograph of C-2.[13] These show that both parapegma plates were much more extensively preserved than they are now.[14] The

12 Photographs from Price's 1958 visit to the Museum, in the Adler Planetarium collection, show Fragment C with a small piece broken off of PP2 (as it was in the 1953 photographs and in its present condition). This damage seems to have been repaired at the time, and has no significance for our investigations.

13 The 1918 photograph of C-1 is spoiled by bad exposure and lighting, at least in Rehm's print. See also Theofanidis [1927-1930], "99" [correct pagination: 91] and 1934, 144 for rather crude line drawings of C-2 that appear to confirm that the fragment still had the 1905-1918 outline, as well as a transcription by Leonardos that includes some text that was no longer on Fragment C after the breakage.

14 The breakage must have been accidental, and probably occurred during the emergency

back faces of the parapegma plates on C-2 were covered with a layer of accretion, so that the inscription that is now easily made out on the small remaining exposed surface of PP2 was invisible. This surface was probably cleaned during the 1953 conservation.

For the 1903 state, we depend on the photographs in Svoronos's volume on the Antikythera wreck of C-1 (Fig. S9) and C-2, and Rediadis's verbal description in the same volume. C-2 shows even more accretion material than in the post-1905 state, but apparently no other distinct features. C-1, on the other hand, has layers of material almost entirely covering the surfaces that were exposed in 1905. These layers were carefully removed in the c. 1905 conservation work.

During his 1958 visit, Price saw Fragment G, a fairly extensive piece of inscribed plate assembled from many smaller pieces — in his notes, he calls it the "jigsaw fragment". Probably through study of the early photographs, he realized that G had originally been the great part of the layer of material in the 1903 photograph of C-1 that concealed the parapegma plates. Though he says little about Fragment G in his 1959 *Scientific American* article, he alludes to it as the "front door" of the Mechanism, and a schematic diagram of his reconstruction of the original relative positions of the major fragments shows that he had established that, when it was part of C, G's inscription —the Front Cover Inscription[15]— was facing forwards like the inscription on PP1, but was oriented the other way up.[16] In 1974 he presented this hypothesis explicitly if rather circumspectly.[17] Close inspection of the 1903 photograph confirms that Price had the relationship of G and C exactly right.

Relying on the criteria of lettering size, line spacing, and characteristic vocabulary,[18] we can identify four small fragments as having belonged to the Parapegma Inscription (Fig. 3.6). Three of these were already identified as such by Stamires and Price.[19]

wartime storage (IAM 2.1).

15 See IAM 6.

16 Price 1959, 65 and diagram on 62-63. This diagram (as well as a photograph in the Adler Planetarium collection from 1958 showing Price examining the fragments) shows a slightly larger Fragment G than now exists, incorporating the present Fragment 29 at its bottom left.

17 Price 1974, 21-22 with figure 10. The statement on p. 47 that Fragment G was assembled from pieces removed from Fragment *B* is presumably a typographical error.

18 See IAM 1.4.

19 Price 1974, 46, fig. 35.

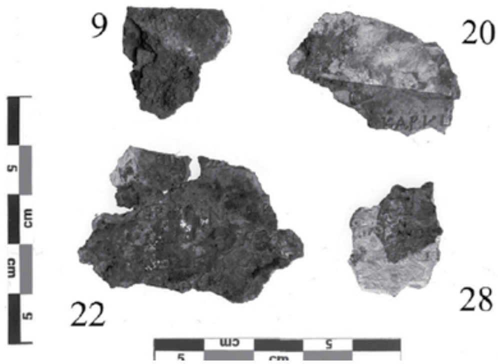

Figure 3.6: *Fragments 9, 20, 22, and 28*
(Images: National Archaeological Museum, Athens, photographer: Kostas Xenikakis, copyright: Hellenic Ministry of Culture and Sports/Archaeological Receipts Fund)

Fragment 9. Width 21 mm, height 23 mm. A piece of plate with parts of four lines of inscription (letter height about 2.3 mm, baseline-to-baseline about 4.7 mm), almost entirely concealed by a layer of other material; slightly above the top line is a straight edge parallel to the text, which must have been the original top edge of the plate. Fragment 9 does not appear in any photographs before 2005, and is not mentioned in *Gears from the Greeks*.

Fragment 20. Width 36 mm, height 27 mm. The fragment is composed of two pieces of plate that slightly overlap. One of these, which bears part of one line of inscription (letter height about 2.5 mm), has a straight upper edge running parallel to the text; this would have been the original edge of the plate. Between the left margin of the text and this edge, a small circular hole is drilled through the plate, and a small object having a rectangular cross-section is lodged in the hole, seemingly the remains of a peg or rivet. The edge of the other plate that overlies this edge at a slight angle (about 10°) is also straight and thus an original edge. In the transcription of the parapegma inscription in *Gears from the Greeks* this is fragment (ii).

Fragment 22. Width 47 mm, height 32 mm. A piece of plate, preserving no original edges, with parts of six lines of inscription (letter height about 2.5 mm, baseline-to-baseline about 5.3 mm). This is Price's fragment (v).

Fragment 28. Width 20 mm, height 25 mm. A piece of plate, preserving no original edges, with parts of four lines of inscription (letter height about 2.3 mm, baseline-to-baseline about 5.3 mm). This is Price's fragment (iv), but Price and Stamires evidently had difficulty making out the text, and their attempt at a transcription has the fragment oriented the wrong way up.

3.3 Previous transcriptions

During his visits to the Museum in 1905 and 1906, Rehm transcribed PP1 col. ii, as well as the single word, Παχών, on the Egyptian Calendar Scale.[20] His reading of Παχών was reported in print in a monograph on the Mechanism by K. Rados, but the transcription of the Parapegma Inscription remained in manuscript, and in fact Rehm never referred to it in any of his substantial later publications on parapegmata.[21] Meanwhile in the 1920s the epigrapher Vasileios Leonardos read part of the parapegma text —not very accurately— for Ioannis Theofanidis, who included it in his encyclopedia article on the voyages of St. Paul with a terse interpretation of the text as instructions for determining the season of the year.[22]

In 1958, Price and Stamires transcribed the texts that they could make out on what was left of the plate and the dials, and Price published a drawing of Fragment C with these transcriptions the following year.[23] Price also discovered that the lines of the Parapegma Inscription were keyed to graduations on the dial by means of a series of alphabetically ordered index letters. Subsequently he gained access to Rehm's papers, and the transcriptions that he included in his 1974 *Gears from the Greeks* incorporate Rehm's readings from the parts of Fragment C that had broken off.[24] In this work Price also drew attention for the first time to the survival of other bits of parapegma text visible on the back face of the other plate stuck to the front dial on Fragment C as well as on three small fragments. As we have already noted, he conjectured that the Parapegma Inscription was laid out in a two-column format on two rectangular plates that were originally situated above and below the front dial, and he attempted a tentative and partial reconstruction of the parapegma text.

20 The extant transcriptions of the Parapegma Inscription are Rehm 1905, 21 and Rehm 1906b, 3. Both must have been copied from manuscript transcriptions that have not been located. Price 1974, 46 incorporates readings from Rehm's 1906 version, a handwritten copy of which (not quite identical to the one in Rehm 1906b) is in the file of Price's transcriptions at the Adler Planetarium, Chicago. The Παχών reading is first reported, with the first letter indicated as illegible, in Rehm 1905, 19, and with all letters shown as clear in Rehm 1906a, 86.

21 Rados 1910, 34. Rados learned of the reading from a lecture that Karo gave at the Deutsches Archäologisches Institut in Athens on December 6, 1906 about the Antikythera wreck, in which he presented part of Rehm's unpublished research on the Mechanism (Rados 1910, 1, note 1); see IAM 2.1.

22 Theofanidis [1927-1930] "99" [correct pagination: 91]. The text is reproduced in Theofanidis 1934a, 144, where it is described as "une instruction pour les levers et couchers des astres du Zodiaque".

23 Price 1959, 65.

24 Price 1974, 18 (dial inscriptions), 46, and 49 (parapegma).

The provisional new texts of inscriptions on the Mechanism published in 2006 did not include the Front Dial and Parapegma Inscriptions.[25] A partial restoration of these inscriptions based on a preliminary version of the texts published here was incorporated in T. Freeth's digital reconstruction of the Mechanism's front face as published in 2012.[26]

25 Freeth et al. 2006.

26 Freeth & Jones 2012, Fig. 4. Dr. Freeth participated in discussions with the present authors concerning the Parapegma Inscription during 2008-2012, and we gratefully acknowledge his responses to proposed readings and provision of CT images.

3.4 Transcription and translation

In sections 3.7 and 3.8 we will show that Fragments 20 and 22 can be exactly placed as parts of PP2 that were still on Fragment C in its post-1905 state, and that Fragment 9 was originally a piece from the top of PP2, to the left of what remained of PP2 on the post-1905 state of C. Our transcription assumes these placements. On the other hand it remains uncertain where Fragment 28 belonged (see 3.11), so we present its text as an unplaced fragment. More generally we adopt a cautious and minimal approach to restoring the Parapegma Inscription's text; more extensive restorations dependent on hypothetical elements are offered in sections 3.9-3.11.

The transcriptions are based on the 2005 CT, PTM, and photographs, and on the 1905 photograph of C-1 (supplementary Fig. S10). Letters that are extant or legible only in the 1905 photograph are underlined.[27] For the Parapegma Inscription, the notations x+1 etc. (z+1 etc. for Fragment 28) are used to number lines when it is not visually evident how many lines preceded the top line of a surviving sequence. The fragments preserving parts of each line of the Parapegma Inscription are indicated in parentheses to the left of the text.

Names of zodiacal signs on the Zodiac Scale

1. Extending from left edge to the 19th graduation of the leftmost (Virgo) sector (counting clockwise from the presumed longer graduation marking the beginning of this sector, which we count as the 1st graduation):
   [Παρθ]ένος
   Virgo

2. Extending from the 9th to the 17th graduation of the next (Libra) sector:
   Χηλαί
   Libra

3. Extending from the 9th to the 20th graduation of the next (Scorpio) sector:
   Σκ̣ορπί̣ος
   Scorpio
   κ̣: entire letter visible but faint | ι̣: indistinct

27 Karo's 1905 photograph of C-1 is the only known photograph to show legibly the part of PP1 col. ii that was subsequently lost to breakage, as well as the small region of the calendar dial exposed in Fragment C's post-1905 state. This area of the dial, with its month-name inscription, is still extant but was in better condition in 1905 than it is now. Other photographs from before 2005 show no details of the inscriptions that cannot be seen at least as well by means of CT or PTM.

4. Extending from the 10th graduation of the next (Sagittarius) sector to the right edge:

Τοξ[ότης]

Sagittarius

Index letters on the Zodiac Scale

Virgo sector (preserved from its 15th graduation on, but surface damaged to the left of the 19th graduation):[28]

To the right of the 19th graduation: Ψ̣

To the right of the 21st graduation: Ω

The index letters in this sector were read from PTM ak32a; they cannot be seen in CT. | Ψ̣: lower portion of a vertical with a broad serif.

Libra sector:

To the right of the 1st graduation: Α

To the right of the 11th graduation: Β

To the right of the 14th graduation: Γ

To the right of the 16th graduation: Δ

Scorpio sector:

To the right of the 1st graduation: Ε

To the right of the 4th graduation: Ζ

To the right of the 17th graduation: Η

To the right of the 22nd graduation: Θ

Sagittarius sector:

To the right of the 1st graduation: Ι

To the right of the 3rd graduation: Κ̣

To the right of the 7th graduation: Λ

Κ̣: entire letter visible but faint

28 Price 1959, 65, reports no index letters in this sector, but Price 1974, 18, reports "with great uncertainty" Ω to the right of the 18th graduation (counting clockwise from the extrapolated 1st graduation as defined above). We suspect that he interpreted the remains of the psi that we report above as the lower right portion of this supposed omega.

Names of Egyptian months on the Egyptian Calendar Scale

1. Extending from the 7th through the 18th graduation of the leftmost (Pachon) sector (counting clockwise from the presumed longer graduation marking the beginning of this sector, which we count as the 1st graduation):
   Παχ̣ών
   Pachon

Indistinct traces of x are visible in the 2005 photograph and PTM (ak32a); the letter is clear in the Karo photograph.

2. Extending from the 10th through the 19th graduation of the next (Payni) sector:
   Παῦνι
   Payni

3. Extending from the 10th through the 21st graduation of the next (Epeiph) sector:
   Ἐπείφ
   Epeiph

Parapegma Inscription
PP1

col. i.

(9) *top margin 2.5 mm.*
1 [Αἰγοκέρως ἄρχ]ε̣ται ἀνα[τέλλειν.]
2 [*v* τροπαὶ χει]μ̣εριναί[. A]
3 [–7– ἐπιτέλ]λ̣ει *v* ἑσ̣[πέριος/περία. *nn*]
4 [–13–]. Ε̣ [
3-4 lines lost

(C) x+1 [ ] IA
—— —— ——

(9) 1 [Capricorn] begins to rise.
2 Winter [solstice. 1]
3 [ ] rises in the evening. [*nn]*
4 [ ]...[
3-4 lines lost

(C) x+1 [ ] 11
—— —— ——

1 Ε̣: serifed top and bottom horizontals, apparently some spread towards right, notch along edge about halfway between the two horizontals; either Ε or Σ
2 Μ̣: apparent upper right end of ascending oblique, meeting a straight vertical (inclining slightly counterclockwise of true vertical) near the top; the bottom of the vertical not preserved | ̣^{2}: serif and very top of vertical
3 Λ̣: lower portion of descending oblique along edge with serif at bottom; Ν appears to be excluded since there is no trace of the right vertical | *v*: one letter | Σ̣: trace of upper left corner along edge
4 ̣^{1}: top of serifed(?) vertical along edge | ̣^{2}: notch along edge at top height, belonging to a serif or gently descending oblique
x+1: this line vertically half-way between col. ii lines x+6 and x+7, and ending immediately to the left of the beginnings of those lines

col. ii.

— — —

(C) x+1 [Κ *v* –12–] ̣ Ι ἐσ̣[π]ερ̣[ί]α̣[*nn*]
x+2 Λ *v* Ὑάδ̣[ες δύον]ται ἐσ̣περίαι̣. *v* ΚΑ
x+3 Μ *v* Ταῦρο̣ς̣ ἄ̣ρχ̣ε̣ται ἀνατέλλειν. Α
x+4 [Ν *v*] Λύ̣ρα ἐ[πιτ]έ̣λ̣λ̣ε̣[ι] ἐσπερία. *v* ΙΑ
x+5 Ξ̣ *v* Πλειὰς ἐπι[τ]έλλει ἐῷι̣α̣. *v* ΙΖ̣
x+6 Ο *v* Ὑὰς ἐπιτέλλει v ἐώια. *v* Κ̣Ε
x+7 Π *v* Δίδυμοι ἄρχονται ἐπιτέλλει̣ν̣. [Α]
x+8 Ρ *v* Ἀετὸς ἐπιτέλλει ἐσπέριο[ς. *nn*]
x+9 Σ *v* Ἀρκτοῦρος δύνει *v* ἐῷι̣ος. *v* Ι̣
bottom margin 7 mm.

— — —

x+1 [Κ] in the evening. [*nn*]
x+2 Λ Hyades set in the evening. 24
x+3 Μ Taurus begins to rise. 1
x+4 [Ν] Lyra rises in the evening. 11
x+5 Ξ Pleiad rises in the morning. 17
x+6 Ο Hyad rises in the morning. 25
x+7 Π Gemini begin to rise. [1]
x+8 Ρ Aquila rises in the evening. [*nn*]
x+9 Σ Arcturus sets in the morning. 10

All lines *v*^{1} (following index letter): average about 2 mm.
x+1 ̣ : serifed right ends of horizontals at top and baseline level, apparently diverging slightly, and a horizontal or mark just above half height, either Ε̣ or Σ| σ̣: lower left corner and indistinct trace of upper left corner | ρ: very bottom of vertical and serif, faint | *v*^{2}: half a letter
x+2 δ: lower part of descending oblique visible in Karo photograph; Rehm also reads δ | σπ: very indistinct, but π is clear in Karo photograph | ̣ι^{3}: only top of vertical with serif,

faint | v^2: one letter
x+3 ̣ι^{2}: indistinct, along break
x+4 v^2: two letters
x+5 Ξ̣ : most bottom stroke with serif at right end; right portion of middle stroke | ̣ι^{4}: serifed top of vertical stroke | α̣ ^{2}: lower part of serifed ascending oblique stroke | v^2: width of one to two letters | Ζ̣ : top and bottom serifed horizontal strokes, straddling a crack; vertical stroke would coincide with crack
x+6 v^2: one letter | v^3: width of four letters | Κ̣ : serifed vertical, faint traces of left ends of both oblique strokes, close to following Ε
x+7 ι̣ν̣: indistinct traces
x+8 v^2: width of one letter | Ε̣: very faint but complete
x+9 v^2: half a letter | ι̣^{2}: indistinct traces | v^3: width of three letters | Ι̣: vertical stroke serifed at both ends, surface damaged to the right

PP2

col. iii.

(C+22) top margin 7.5 mm

	1	[Α *v* Χηλ]αὶ ἄρχονται ἐπιτ̣[έ]λ[λ]ειν.
	2	[*v* ἰσημ]ερ̣ί̣α̣ φθ̣ινοπ̣ω̣ρ̣ινή. *v* Α
	3	[Β *v* –5– ἐπι]τέλλουσιν [ἐ]σ̣π̣έριοι. ΙΑ
	4	[Γ *v* –6– ἐπιτ]ελλε[ι ἐσ]περία. ΙΔ
(22)	5	[Δ *v* –14– ἐπι]τ̣έλ̣λει. ΙϹ
	6	[Ε *v* Σκορπίος ἄρχεται ἐπιτέλ]λ̣ειν. Α̣

—— —— ——

(C+22)	1	[Α]	Claws (i.e. Libra) begin to rise.
	2	[	] Autumnal equinox. 1
	3	[Β	] rise in the evening. 11
	4	[Γ	] rises in the evening. 14
(22)	5	[Δ	] rises [in the morning/evening.] 16
	6	[Ε	Scorpio begins] to rise. 1

—— —— ——

1 τ̣^{2}: left portion of horizontal, and serifed bottom of vertical
2 ρ̣ι̣α̣: complete but blurry | θ̣: indistinct traces | π̣: right end of horizontal and short right vertical | ω̣: complete but blurry | ι̣^{4}: top of serifed vertical | v^2: width of one letter
3 σ̣^{2}: bottom left corner | π̣^{2}: bottom of right vertical
5 τ̣^{2}: horizontal along edge
6 [ἐπιτέλ]λ̣ειν: or [ἀνατέλ]λ̣ειν | 6 λ̣^{2}: apex along edge | Α̣: top parts of ascending and descending obliques

col. iv.

(22+20) *top margin 7.2 mm*
1 Μ *v* Καρκί[νος ἄρχεται ἐπιτέλλειν.]
(22) 2 [τροπαὶ θεριναί. Α]
3 Ν *v* Ὠρί̣[ων ἐπιτέλλει ἐῷιος. *nn*]
4 Ξ *v* Κ̣ύων̣ [ἐπιτέλλει ἐῷιος. *nn*]
5 Ο *v* Ἀετ[ὸς δύνει ἐῷιος. *nn*]
6 Π̣ *v* Λ̣[έων ἄρχεται ἐπιτέλλειν. Α]
— — —

(22+20) 1 Μ Cancer [begins to rise.]
(22) 2 [Summer solstice. 1]
3 Ν Orion [rises in the morning. *nn*]
4 Ξ Sirius [rises in the morning. *nn*]
5 Ο Aquila [sets in the morning. *nn*]
6 Π Leo [begins to rise. 1]
— — —

All lines v^1 (following index letters): average about 2.5 mm
1 [ἐπιτέλλειν]: or [ἀνατέλλειν]
2 ν̣ή: the surface of the plate bearing the writing is twisted about 30° counterclockwise from horizontal
3 ι̣^{1}: bottom serif of vertical stroke
4 Κ̣: descending oblique with serif | ν̣: left vertical with serif
6 Π̣: horizontal | Λ̣: ascending oblique with bottom serif, and top of descending oblique | [ἐπιτέλλειν]: or [ἀνατέλλειν].

Unplaced fragment (Fragment 28).

— — —
(28) z+1 [ ] Κ̣[*n?*]
z+2 [–*n*– ἄρχεται ἐπιτ]έ̣λλειν. [Α]
z+3 [–*n*+6– ἑσπέ]ριος. *v* Ι̣C
z+4 [–*n*+6– ἑσπε]ρία̣. *v* Κ[*n?*]
z+5 [–*n*+11–]Ε̣ . . [ ]
— — —

— — —
(28) z+1 [ ] 2[*n?*]
z+2 [begins] to rise. [1]
z+3 [ ] in the evening. 16
z+4 [ ] in the evening. 2[*n?*]
z+5 [ ] ... [ ]
— — —

z+1 Κ̣: apparently a descending oblique with serif, and faint lower portion of vertical, but it is not certain that these are not accidental marks
z+2 ε̣^{3}: trace of bottom horizontal along edge
z+3 *v*: two letters. Ị: top of a serifed vertical
z+4 ά̣: lower end of ascending oblique with serif | *v*: three letters
z+5: The original surface of the plate has been stripped away in the region around this entire line, and the traces are very shallow and faint. | Ẹ: top of vertical, whole of serifed top horizontal, right ends of middle horizontal, and right end of serifed bottom horizontal, all rather faint | ̣ ̣: very uncertain traces

3.5 Parapegmata

The term "parapegma" is used in both ancient texts and modern scholarship with two distinct though overlapping meanings.[29] On the one hand any Greco-Roman artefact furnished with a series of peg-holes standing for units of time, especially days, composing a repeating cycle can be called a parapegma; the holes are typically accompanied by inscriptions or pictorial elements associating the stages of the cycle with something else, for example the deities associated with the seven days of the planetary week. The ancient Greek word *parapêgma,* meaning *"beside-pegging,"* must have originally referred to this kind of object. On the other hand, a text written on any medium that lays out in chronological order an annually repeating cycle of days associated with events and phenomena, among which dates of first and last visibility of stars and constellations (referred collectively as *phaseis*, "appearances," or as *phaseis* and *krypseis*, "disappearances") figure prominently, is a parapegma. What connects the two uses of the word is a category of public inscription, specimens of which dating from the second or early first centuries BC have been found at Miletos, that used a series of peg-holes to represent the days in a solar year, with inscriptions next to many of the holes describing astral and other events associated with the corresponding days.[30] The Parapegma Inscription of the Mechanism is a parapegma in the second sense.

One of the best preserved and most characteristic parapegmata is a text, probably composed during the Hellenistic period (certainly not before the late third century BC), that is appended to the end of Geminos's *Introduction to the Phenomena* (mid first century BC) in the medieval manuscript tradition; whether Geminos was responsible for its presence there is an open question, but it is conventionally referred to as the Geminos Parapegma.[31]

29 Parapegmata of both kinds are surveyed and catalogued in Lehoux 2007.

30 Fragments of two parapegma inscriptions were found during the German excavations at Miletos in 1902-1903. One of them, probably laid out in a format of one column for each zodiacal month (notwithstanding Rehm's objection, Rehm 1904, 753), is represented by IMilet. inv. 456A, 456D, and 456N. 456C, which contains a dedication by Epikrates son of Pylon and an introductory text with different but similar letter forms, and traces of peg holes along the right side, probably also belongs to this parapegma. Epikrates son of Pylon is also known from the dedication of his statue base, *IMilet.* 331, and, according to a likely restoration of his name in *IMilet.* 107, he held the honorary office of stephanephoros in a year that must have fallen within the gap between 184/183 BC and 89/88 BC in the preserved lists of Milesian stephanephoroi (he was not stephanephoros *in* 89/88 BC as stated by Lehoux 2005, 134). The other Milesian parapegma inscription, laid out in a format of two zodiacal months per column, is represented by 456B. The inscriptions were published in Diels & Rehm 1904 and Rehm 1904, and again more conservatively in Lehoux 2005.

31 Complete translation in Evans & Berggren 2006, 231-240.

We shall frequently have occasion to refer to this text. It describes recurring events in a solar year beginning with the Summer Solstice and divided into twelve parts or "zodiacal months," each beginning with the Sun's entry into a new zodiacal sign. Within each zodiacal month, events are assigned to day numbers counted from the Sun's entry as "day 1." The section for Taurus is a typical specimen:

> The Sun traverses Taurus in 32 days.
>
> On the 1st day, according to Eudoxos, Orion sets acronychally; rains. According to Kallippos Aries finishes rising; rains, often also hail.
> On the 2nd day, according to Euktemon, Sirius is hidden; and hail occurs; on the same day Lyra rises. According to Eudoxos, Sirius sets acronychally; and rain occurs. According to Kallippos, the tail of Taurus rises; southerly winds.
> On the 7th day, according to Eudoxos, rain occurs.
> On the 8th day, according to Euktemon, Capella rises in the morning; fair weather; it rains with southerly water.
> On the 9th, according to Eudoxos, Capella rises in the morning.
> On the 11th, according to Eudoxos, Scorpius begins to set in the morning; and rain occurs.
> On the 13th, according to Euktemon, the Pleias rises; beginning of summer; and weather-change. According to Kallippos, the head of Taurus rises; weather-change.
> On the 21st, according to Eudoxos, the whole of Scorpius sets in the morning.
> On the 22nd, according to Eudoxos, the Pleiades rise; and weather-change.
> On the 31st, according to Euktemon, Aquila rises in the evening.
> On the 32nd, according to Euktemon, Arcturus sets in the evening; weather-change. According to Kallippos, Taurus finishes rising. According to Euktemon, the Hyades rise in the morning; weather-change.

The visibility events associated with asterisms (stars, star clusters, and constellations) in the Geminos Parapegma and other documents of its kind are consequences of the fact that all stars rise and set a few minutes earlier every day than the day before. Four kinds of visibility events are recognized:

> Morning rising: the first occasion when the asterism can be seen close to the eastern horizon before sunrise, after an interval of some days on which the asterism could not be seen at that time.[32]

32 Geminos 13.9, ed. Manitius 148, defines the morning rising as "when (the star) rises enough in advance (of the Sun) so that the star has escaped the Sun's rays and its rising can be beheld."

Evening setting: the last occasion when the asterism can be seen close to the western horizon after sunset, or perhaps the following day, when the asterism can no longer be seen; the verb *kryptesthai* ("to disappear") is sometimes employed instead of *dynein/dynesthai* ("to set").[33] In ancient texts, e.g. in the line quoted above for the first day in the zodiacal month of Taurus, this event is sometimes designated "acronychal setting," meaning setting at nightfall.

Evening rising: the last occasion when the asterism can be seen rising at the eastern horizon after sunset, or perhaps the following day, when it is already above the horizon when first sighted.[34] This event is also called "acronychal rising" both in ancient texts and modern terminology.

Morning setting: the first occasion when the asterism can be seen setting below the western horizon before sunrise, following days on which the asterism is still above the horizon at dawn.[35] In modern terminology (but not in ancient parapegmata) this event is sometimes called "cosmic rising".

Very occasionally, a parapegma will also record dates when a star becomes "conspicuous" (*phaneros*) a few days after its morning visibility. For constellations, distinct dates may be specified for when the constellation is considered to be visible for the first or last time in its entirety, when it begins to be visible or invisible, or when specified stars within it are visible for the first or last time. Some parapegmata, including the Geminos Parapegma but apparently not the Mechanism's inscription, intermittently leave out the indication of whether it is a morning or evening event.

The Geminos Parapegma exhibits features that are frequently encountered in other parapegmata, though as it happens, *not* in the Mechanism's Parapegma Inscription:

33 Geminos 13.18, ed. Manitius 152: "when some star is beheld setting after the Sun after sunset" (presumably for the last time). According to Geminos's definitions, the evening events are symmetric with their morning counterparts, that is, the morning rising and evening setting have the asterism visible close to the horizon respectively for the first and last time, while the morning setting and evening rising have the asterism seen crossing the horizon respectively for the first and last time. Since the evening events are defined as the last evening when a certain criterion is met, an observer would have to wait one more night to confirm that either evening event has taken place.
34 Geminos 13.13, ed. Manitius 150: "when (the asterism) first is beheld as having escaped the rays of the Sun after sunset."
35 Geminos 13.16, ed. Manitius 152: "when the star is seen setting for the last time before the rising of the Sun."

statements of weather changes, and attributions of both the astral and meteorological statements to specific authorities, mostly the well known Greek astronomers Euktemon, Eudoxos, and Kallippos. (In Lehoux's nomenclature, a parapegma containing weather phenomena is "astrometeorological," and one that cites authorities is "attributive".) The Greek parapegma tradition regularly omitted a kind of information that might seem essential: the geographical locations for which the statements are supposed to be valid. Only the parapegma that Ptolemy published in his *Phaseis*, which is an effort at reform of the genre, provides geographical data.[36] Also characteristic is the lack of clear definition for the asterisms in the visibility statements: constellations, including some large ones such as Orion, and clusters such as the Pleiades, are more commonly cited than single stars, and we are usually not told the criteria for determining when such an object is visible in whole or part.[37] (Again, Ptolemy breaks with tradition by restricting consideration to individual bright stars.)

The reason for inscribing a parapegma on the Mechanism, the derivation of its contents, and its relation to other surviving parapegmata are questions beyond the scope of the present paper. It is worth remarking, however, on the centrality of parapegmata in the history of Greek astronomy. If the very frequent citations of Euktemon and Eudoxos in the extant parapegmata are authentic, Greek astronomers were compiling the kinds of statement recorded in parapegmata as far back as the fifth century BC, while the format as a serial list of days in an annual cycle is attested already around 300 BC in the Greek papyrus *P. Hibeh* 1.27.[38] While mathematical modeling of the motions of the heavenly bodies acquired greater importance in the astronomy of late Hellenistic and Imperial times, we nevertheless find the great second century BC astronomer Hipparchos among the authorities for parapegma data, and Ptolemy as the author of an extant parapegma. The tradition was still alive in late antiquity.

36 Heiberg 1907, 66-67.

37 Occasionally a specific part (i.e. star) of a constellation is indicated, e.g. "the shoulder of Orion rises," in contrast to the less specific "Orion begins to rise" or "Orion rises entire."

38 *P. Hibeh* 1.27 (published in Grenfell & Hunt 1906) has unusual features in its use of the Egyptian calendar and its inclusion of religious festivals and calculated lengths of daylight, perhaps reflecting its Greco-Egyptian provenance as much as its early date. Since the Egyptian calendar year had a constant length of 365 days, the dates associated with astronomical statements in the papyrus would have rapidly lost their validity. The *word* "parapegma" first occurs in another papyrus dating from the second century BC, *P. Ryl.* 4.589 (published in Hunt *et al.* 1911-1952, vol. 4), though the surviving part contains a schematic lunisolar calendar but no astral and meteorological statements. Geminos is the earliest extant author who employs the word in the sense in which we use it.

3.6 The Parapegma Inscription: PP1 col. ii

The parapegma text was physically laid out in several distinct sections whose states of preservation vary considerably. We shall begin with the text on C-1, which is conspicuous in the fragment's present condition and much of which is easily legible (Figs S3 and 3.7); still more of it was preserved in Rehm's time. Our transcription differs from its predecessors in several minor details and one that is more significant: previous transcriptions did not take note of the presence of numerals at the ends of some lines. We will explain the meaning of these numerals when we come to the inscription on PP2 (section 3.7). We believe that almost every line of the inscription originally ended with such a numeral, and have indicated their expected places in the transcription and translation (where we employ "*nn*" for an undetermined numeral) even when no trace is visible. Because of the extreme distortion and damaged surface of the rightmost part of the plate, only the numeral at the end of line 2 is easily seen in a conventional photograph or by direct inspection. We only noticed the numerals here because our study of PP2 had led us to expect them. The previous transcriptions also did not record two very conspicuous letters IA at the left edge of the present fragment, at a height intermediate between lines 6 and 7, and having slightly smaller letter height than the main body of the inscription. These letters must have belonged to another column of the inscription to the left of the one under consideration. We will refer to this previously unrecognized left column as col. i and the better preserved right column as col. ii.

Figure 3.7: *Fragment C, CT composite image of the Parapegma Inscription on PP1 (Image: Antikythera Mechanism Research Project)*

The text of col. ii consists of a series of simple sentences, each preceded by a letter of the Greek alphabet and followed by a numeral. As Rehm already noted, the letters, as they were preserved in his time, ran in alphabetic order from lambda through sigma. The first partially preserved line would originally have had the letter kappa, so that the extant text should have been preceded somewhere by a further nine statements, labelled alpha through iota. The statement labelled sigma is near the bottom edge of the plate, which is clearly an original edge since it is straight and parallel to the lines of text. If there were further statements labelled tau and so forth, they would have had to be inscribed somewhere else.

Six of the preserved statements, and probably a seventh in the less well preserved line x+1, follow the fixed pattern *N V A,* where *N* is the name of an asterism (star, constellation, or star cluster) standing as the subject of the sentence, *V* is the appropriate present indicative form of a verb meaning "rises" (ἐπιτέλλω) or "sets" (δύνω or δύομαι), and *A* is an adjective, modifying *N*, meaning "in the morning" or "in the evening." Rehm recognized that these were statements characteristic of a Greek parapegma and signifying the annually recurring event when the asterism makes its first visible rising or setting either just before sunrise or just after sunset. The listed events are in more or less correct chronological order and fall within the interval between Vernal Equinox and Summer Solstice. The asterisms in this section of the Parapegma Inscription, as well as those in the one other fragment (Fragment 22) that preserves asterism names, all belong to the set of asterisms associated in the Greek parapegma tradition with Euktemon and Eudoxos among other authorities (see section 13). This set comprises fifteen asterisms, many though not all of them characterized by very bright stars; it almost certainly antedates the introduction of the zodiac into Greek astronomy, and Scorpius is the only zodiacal constellation that figures in it.

The statements in lines x+3 and x+7 follow a different pattern *N V I,* where *N* is the name of a constellation standing as subject, *V* is the appropriate present indicative form of the verb ἄρχομαι, meaning "begins," and I is the infinitive of a verb meaning "to rise" (ἐπιτέλλειν or ἀνατέλλειν, apparently used synonymously). No adjective follows, but for these events to fall into correct chronological sequence with the other listed astral events, these statements must refer to the morning. This special treatment appears to be conferred only on constellations belonging to the zodiac. Two possible interpretations of these lines will have to be considered. On the one hand they may refer to the actual constellations Aries, Taurus, etc., in which case the events in question would probably be the dates when the first stars of these constellations were supposed to make their first visible risings. Alternatively, they may refer to the zodiacal *signs*, the 30° sectors of the ecliptic (such as are marked on the Zodiac Dial Scale) named for the constellations that were roughly aligned with them; in this case, since the signs are not visible objects, the events must be the *ideal* morning risings of the beginnings of the signs, i.e. the dates when the Sun enters each sign so that the first (westernmost) point of the sign crosses the eastern horizon precisely at sunrise. In this case, these lines would mark the beginnings of zodiacal months. As Rehm noted, the Geminos Parapegma contains similarly worded statements attributed to Kallippos, and these definitely refer to the zodiacal constellations, not to the signs.[39]

As we have already remarked, parapegmata are extant in the form of publicly displayed inscriptions on stone, and in these the single days of the solar year are represented by drilled holes that were evidently meant to hold a movable peg indicating the current day. If a hole had a statement inscribed beside it, that statement described the astral or meteorological events associated with that day, while days that had no associated events were represented by holes unaccompanied by text. Parapegmata in manuscript form typically numbered the days within subdivisions of the year, e.g. within the twelve zodiacal months or the months of a non-lunar calendar such as the Egyptian or Roman calendar; in such texts only the days having associated events were listed, according to the day number in the zodiacal or calendar month. Rehm supposed that the index letters of the parapegma inscription corresponded to matching letters inscribed on a dial scale distinct from the Calendar Dial Scale that he had seen on C-1, and that the function of the letters was to indicate the date of each astral event.[40] His conjecture turned out to be essentially correct: when Price saw Fragment C in its present state, with part of the Zodiac Dial Scale exposed, he discovered that it bore the irregularly spaced index letters that we have transcribed above, and realized that they were the counterparts of the index letters in the parapegma inscription. The Calendar Dial Scale, meanwhile, turned out to be movable with respect to the Zodiac Dial Scale, reflecting the shifting relationship of the 365-day Egyptian year to the natural seasons. Thus the astral events were associated with degrees of the Sun's longitudinal motion through the zodiac, not with time units.

Price noticed an anomaly in the distribution of the astral events apparently implied by the index letters:[41]

> "I feel that… the phenomena fall too thickly in the first part of the alphabet, but there are too few of them for the available letters in the second part… there is some mismatch or misplacement that I cannot understand… the problem seems to be unresolvable with this little evidence."

The part of the parapegma in the preserved part of PP1 col. i comprises nine phenomena, all falling between the Vernal Equinox and the Summer Solstice. Since the first of the nine was lettered kappa, one would expect there to have been nine phenomena in

39 Rehm 1905, 21, pencilled addition in bottom margin: "Speziell kallippische Phase!"

40 Rehm 1905, 19-22. Rehm mistakenly identified this second scale as the scale of what we now know as the Saros Dial, partly preserved on A-2.

41 Price 1974, 49.

the lost preceding part of the list, lettered from alpha through iota. But Price had found alpha through epsilon on the Zodiac Dial Scale, distributed over the interval from the first degree mark of Libra to the first degree mark of Scorpio, that is, over about thirty days starting about the Autumnal equinox. That would leave just four phenomena to be distributed over an interval of about 150 days from the point where the Zodiac Dial Scale could no longer be seen to the Vernal Equinoctial Point about the beginning of Aries, a much lower density of phenomena than in the preserved stretches. Six letters of the Greek alphabet, tau through omega, were left for the remaining quarter year, from about the Summer Solstice to about the Autumnal Equinox, which seemed acceptable, but they would have had to be inscribed somewhere else since the sigma line on PP1 was clearly at the bottom of the plate.[42]

42 In *Gears from the Greeks* Price assumes that the Parapegma Inscription comprised a single, complete, run through the 24 letters of the Greek alphabet. Unpublished notes in Price's file of notes on the Mechanism's inscriptions, now at the Adler Planetarium, show that at some stage he had contemplated the possibility that there were multiple alphabetic sequences.

3.7 PP2 cols. iii and iv

The straight top edge of the part of PP2 that is extant on Fragment C is clearly the original edge of the plate. Price and Stamires produced the first transcription of the parapegma text inscribed on its back face, but it was necessarily limited to the two parts of lines visible on the small exposed portion. With the aid of CT we can read the entire surviving text on this piece of plate, comprising parts of four lines starting slightly below the edge and running parallel to it (Fig. 3.8, left).

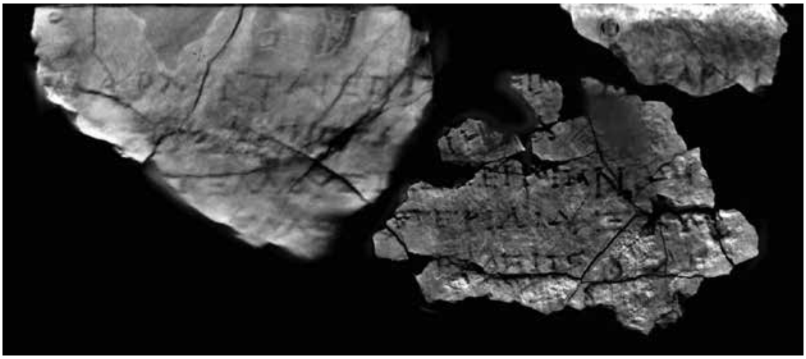

Figure 3.8: *CT composite image of the Parapegma Inscription on PP2 comprising (from left to right) Fragments C, 22, and 20*
(Images: Antikythera Mechanism Research Project)

Fragment 20's composition from two slightly oblique and slightly overlapping pieces of plate suggests that it preserves bits of both PP1 and PP2 from the post-1905 state of Fragment C, around the place where the edges of the two plates met and crossed; we have confirmed this through careful comparison of surface features of Fragment 20 (on the back face with respect to the inscription) with the Karo photograph of C-1 (supplementary Fig. S10) in this region.[43] Surface features of the back face of Fragment 22 are easily matched with the lower left corner of PP2 in Karo's photograph.

Hence we can read or restore a substantial part of the top five lines of PP2, with slight traces of a sixth line (Fig. 3.8). One structural feature becomes immediately obvious: the parapegma text on this plate was laid out in two columns, the left one of which we will refer to as col. iii and the right one as col. iv. We have the ends of the top lines of col. iii, and the beginnings of the lines of col. iv. In both columns, the top line gives one of the zodiacal sign statements,

43 Price 1974, 46 indicates a guess that Fragment 20 belonged to PP2, but thought that it came from the upper edge of the plate to the *left* (as one would view the inscribed face) of the part surviving on C-2.

and there is something anomalous about the second line: no index letter or visible text in col. iv, and a reference to the Autumnal Equinox in col. iii. Putting together the information that we have, we can plausibly hypothesize that the dates when the four signs Aries, Cancer, Libra, and Capricorn were stated to "begin to rise" were also marked, in an *indented* second line, as the equinoxes and solstices. This leads us to several conclusions:

- The "begins to rise" statements must refer to the zodiacal signs, not the zodiacal constellations, since the irregular intervals between the first morning risings of the constellations would not coincide with the solstices and equinoxes. This is confirmed by the fact that on the Zodiac Dial Scale, there are index letters next to the initial graduation of the three signs Libra, Scorpio, and Sagittarius whose beginnings are preserved; in the corresponding part of the Parapegma Inscription these would have been "begins to rise" statements.

- The solstitial and equinoctial points are considered to be placed at the beginnings of their zodiacal signs, as in other Greek parapegmata and astronomical authors (e.g. Ptolemy), rather than say at 8° or 10° into the signs, as in Greco-Roman sources influenced in this respect by Babylonian mathematical astronomy.

- A statement "N begins to rise" is equivalent to statements of the form "the Sun in N" found in other parapegmata, marking the beginning of a zodiacal month.

- The complete parapegma inscription was laid out in four sections corresponding to the quarters of the year beginning with the solstices and equinoxes. Each quarter comprised three zodiacal months.

- The last sign of PP2 col. iv is Virgo. About half this sign is extant on the Zodiac Dial Scale, on which two index letters psi and omega can be read. Hence this column's events were lettered from mu through omega, making a total of thirteen events and fourteen lines.

- The first sign of PP2 col. iii is Libra, the sign whose beginning is the autumnal equinoctial point. Hence this part of the inscription too corresponds to an extant part of the Zodiac Dial Scale, and the index letters of col. iii can be restored from the letters on the dial as running from alpha at least as far as lambda, totalling eleven events and twelve lines.

- One can presume at least two missing lines in PP1 col. ii above the present line x+1, for "Aries begins to rise" and "Vernal Equinox." The index letter of this event was not later in the alphabet than iota. Thus the three consecutive astronomical seasons spring, summer, and autumn were respectively on PP1 col. ii, PP2 col. iv, and PP2 col. iii. The section beginning with Capricorn and the Winter Solstice remains to be accounted for.

We turn now to the numerals, written in slightly smaller letters after the ends of the statements in col. iii. Here we are lucky, since lines 1-2 have been identified as signifying the Sun's entry into Libra, so that the entire col. iii corresponds to a preserved portion of the Zodiac Dial Scale, where we have index letters marking phenomena at the 1st, 11th, 14th, and 16th division marks of Libra and the 1st division mark of Scorpio — exactly matching the numerals in the parapegma inscription. This observation leads to a choice of two interpretations of the numerals in the inscription:

- The numerals could simply be the numbers of the graduations on the Zodiac Dial Scale where the index numbers were inscribed. They would thus represent the Sun's longitude in degrees within the currently occupied zodiacal sign, counting the first degree in the sign, what we would call 0° or perhaps more accurately the interval from 0° up to 1°, as "degree 1." Such numerals would be a redundant tabulation of information that could also be read from the dial.

- The numerals could be day numbers counted from the first day of the current zodiacal month, like the day numbers in the Geminos Parapegma. Since the Sun always spends 30±2 days in a zodiacal sign, the day numbers of phenomena would differ from the degree numbers by at most 2 by the end of a month, and towards the beginnings of any month they would be equal. Libra would likely have been allotted 30 days, so that the degree and day numbers for that sign would be the same through the whole month.

Since the evidence does not allow us to decide whether the numerals mean degrees or days, we will refer to them as day/degree numerals.

As mentioned above, numerals were not previously noticed at the ends of the statements in PP1 col. ii, but notwithstanding the poor condition of the right extremity of the plate (partly the effect of a pronounced warp caused by pressure or impact), a few can be made out. We presume that a day/degree numeral followed every statement in the parapegma, except that in the case of the double statements at the solstices and equinoxes, the numeral 1 (alpha) appeared only at the end of the second line as in PP2 col. iii lines 1-2.

On the basis of the match of the index letters on the Zodiac Dial Scale with the phenomena in PP2 col. iii we restore the index letters in this part of the inscription as alpha through epsilon. The preserved index letters of col. iv, mu through pi, duplicate part of the sequence in PP1 col. ii. There must, therefore, have been more than one alphabetic sequence. There is nothing surprising in this, since the parts of the parapegma that we have considered so far assign three or four events to each zodiacal sign. If this density was roughly maintained through all twelve signs, we may expect that the total number of events was something around the high thirties or forties, enough to require two partial or complete runs through the Greek alphabet.

3.8 PP1 col. i

We have drawn attention above to the presence of two very clear letters inscribed just against the present left edge of PP1, about halfway in height between col. ii lines x+6 (indexed omicron) and x+7 (pi). From their appearance and position, it appears practically certain that these letters, IA, represent a day/degree number 11 at the end of a parapegma statement, all that remains on the present Fragment C of a column of statements to the left of col. ii. Since the parts of the parapegma pertaining to the seasons beginning with the vernal equinox, summer solstice, and autumnal equinox are already accounted for, this col. i must have contained the season beginning with the winter solstice. We designate the line of col. i to which the surviving numeral belongs as line x+1.

We can see no trace of this left column of parapegma inscription on the Karo 1905 photograph of C-1. The appearance of the left quarter or so of PP1 in the Karo photograph is difficult to interpret, and no other photograph from this period showing PP1 from a different angle has so far been found, except for the badly exposed print of the 1918 photograph in Rehm's collection. In Karo's photograph, the region to the immediate left of lines 2-4 of the preserved column shows a rough surface that could be an accretion layer, and to the left and lower left of this is a region that appears to be perfectly smooth except for an apparently engraved straight line that runs nearly parallel to the more or less straight edge of the plate; this edge forms about a 60° angle with the lower edge of the plate. This smooth region appears somehow to be distinct from the visibly inscribed part of the plate, and we suspect that either the original surface of the plate here had been stripped away or that some layer of material was lying on top of it, perhaps another displaced fragment of plate. The illumination of the photograph is unhelpful at this end of the plate, so that even the IA that we know was there cannot be made out.

Fragment 9 (Fig. 3.9) is part of the top lines of the missing column, preserving the Sun's entry into Capricorn and winter solstice followed by two stellar events.[44] The fragment was not part of PP1 in its post-1905 state. Lines 1-2 of PP1 col. i would have been approximately aligned with the lost top two lines of col. ii, which contained the statement of the Sun's entry into Aries and the Vernal Equinox. Hence Fragment 9 line 3, in its lowest possible position, would have been roughly aligned with line 1 of col. ii, and to allow room for the

44 Fragment 9 cannot be a piece of PP2 col. iv extending the top lines still preserved in Fragment C. Aside from the traces at the left edge of line 2 which are not consistent with the event of this line being the *summer* solstice (see note to line 2), the margin between the upper edge of the plate and the top of line 1 is much smaller than the upper margin in the PP2 fragments.

restored end of Fragment 9 line 1, it has to have been entirely to the left of the edge of PP1 as it was in 1905. It is a near certainty that Fragment 9 was not stored together with the known Mechanism fragments in Price's time.

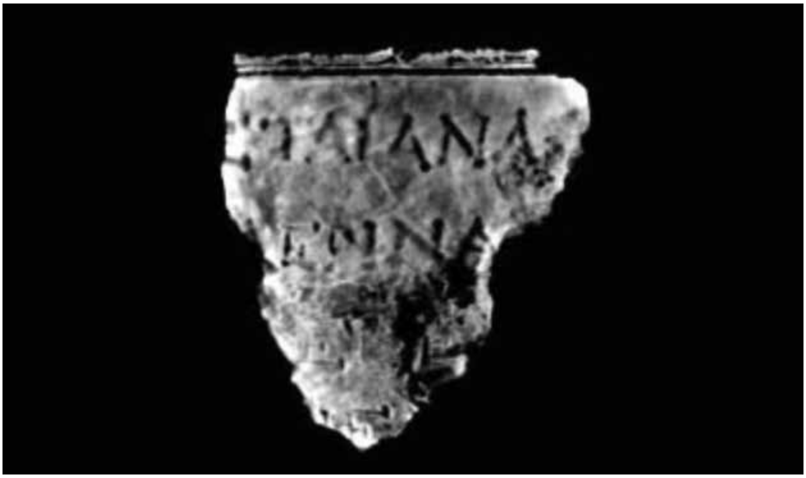

Figure 3.9: *CT composite image of Fragment 9*
(Image: Antikythera Mechanism Research Project)

If col. ii line x+1 immediately followed the lost lines for the entry into Aries and the equinox, then col. ii lines x+6 and x+7 would have been the eighth and ninth lines of this column, and col. i line x+1, of which the day/degree numeral 11 is extant about halfway between col. ii lines x+6 and x+7, would almost certainly have been either the eighth or the ninth line of col. i, depending on whether the line spacing of the column was slightly looser or slightly tighter than that of col. ii. The spacing of the four extant lines in Fragment 9 is in fact significantly greater than the average in col. ii, so it is more likely that col. i line x+1 was the eighth line. In any case, col. i has to have contained statements of at least seven events with distinct index letters.

3.9 The layout of the Parapegma Inscription

If PP1 col. ii contained no events between the Vernal Equinox and the event of line x+1, the index letter corresponding to the Vernal Equinox was iota; otherwise it would have been an earlier letter of the alphabet. PP2 col. iii's events certainly accounted for a series of index letters from alpha through lambda, all of which are visible on the corresponding part of the Zodiac Dial Scale. PP2 col. iv had events with index letters beginning with mu and extending to omega (index letter preserved on the Zodiac Scale). We can thus provisionally summarize the contents of the four columns of parapegma text as follows:

PP1 col. i	PP1 col. ii
Capricorn – Pisces	Aries – Gemini
index letters: at least eight	iota (or earlier) – sigma
≥ 9 lines	≥ 11 lines
PP2 col. iii	PP2 col. iv
Libra – Sagittarius	Cancer – Virgo
alpha – lambda (or later)	mu – omega
≥ 12 lines	14 lines

In PP1, the right column follows immediately after the left in the order of the Sun's motion through the zodiac, but in the PP2 the left column follows the right. Arranged as above, with PP1 above PP2, the four columns run clockwise, whereas if PP2 is put at the top, the columns run counterclockwise. Since the Zodiac Dial Scale, like all the known dials of the Mechanism except the four-year Games Dial of the back face, run clockwise, it makes sense for the inscription, in its original mounting on the Mechanism, to have occupied the parts of the front face above and below the dial as Price conjectured in 1974, with PP1 as the top part and PP2 as the bottom part. In this way, each of the four columns would give information pertaining to the Sun's movement through the nearest quadrant of the Zodiac Dial Scale. As a corollary, the Zodiac Dial Scale would have to have been oriented so that the beginning of Aries was at the top, as Price guessed in 1974.[45]

Fig. 3.10 shows the approximate locations of the surviving parts of the Parapegma Plates according to this hypothesis. What clinches the argument is the bearing mounted behind the

45 Price 1959, 62-63, right figure, shows outlines of Fragments G and C oriented so that the beginning of Cancer (the Summer Solstice) would have been at the top. It is not known what considerations led him to put the beginning of Aries at the top in 1974, though if we take him at his word (Price 1974, 13), he believed that he had confirmed in 1961 the correct physical join between Fragments C and A which would have determined the orientation.

right end of PP1's bottom edge in Fragment C, which turns out to be approximately where the bolt of the presumed upper right sliding catch of the Dial Plate would have projected when in the engaged position.[46] The rivet hole and vestigial feature on PP2 in Fragment C are suitably positioned to be the remains of another bearing which would have received the bolt of the lower left sliding catch of the Dial Plate—which is in fact the extant one! It is thus apparent that the Parapegma Plates were riveted to the wooden frame housing the gearwork by rivets like the one in Fragment 20 (which was at the exact midpoint of PP2's upper edge), while the Dial Plate, when in place, was attached to the Parapegma Plates by the sliding bolts. The projection of the bearings attached to the Parapegma Plates beyond the plates' edge (Fig. 3.4) would have prevented the Dial Plate from falling into the gearwork when it was disengaged.

The approximate dimensions of the original plates can be determined from the known position of the dial, which was centered slightly higher than the geometrical center of the Mechanism's front and back faces. We can estimate the usable height of the upper plate, PP1, as about 65-68 mm, and that of the lower plate, PP2, as about 83 mm.[47] Taking into account the extant margins at the bottom of PP1 and at the top of PP2, this would mean that the columns of PP1 probably could not have contained more than twelve lines, while those of PP2 could have contained fifteen or possibly even sixteen lines. This is consistent with what we previously deduced about the numbers of lines in each column, and confirms that PP1 was indeed at the top.

The alphabetic sequences of index letters obviously cannot have followed the clockwise structure of the inscription's contents. The events in PP2 col. iv follow directly after those of PP1 col. ii in their annual cycle, but the index letters jump back from sigma to mu. Moreover, while the other columns would not seem to have listed more than thirteen events at most, PP1 col. i would have to have had to contain something like twenty events to account for the end of the alphabet begun in PP2 col. iii plus the beginning of the alphabet continued in PP1 col. ii.

46 Precise measurements cannot be obtained for the distance of the bearing from PP1's right edge or for that of the extant sliding catch from the corresponding edge of the Dial Plate because both plates are badly fractured and distorted in those regions.

47 See IAM 1.5.

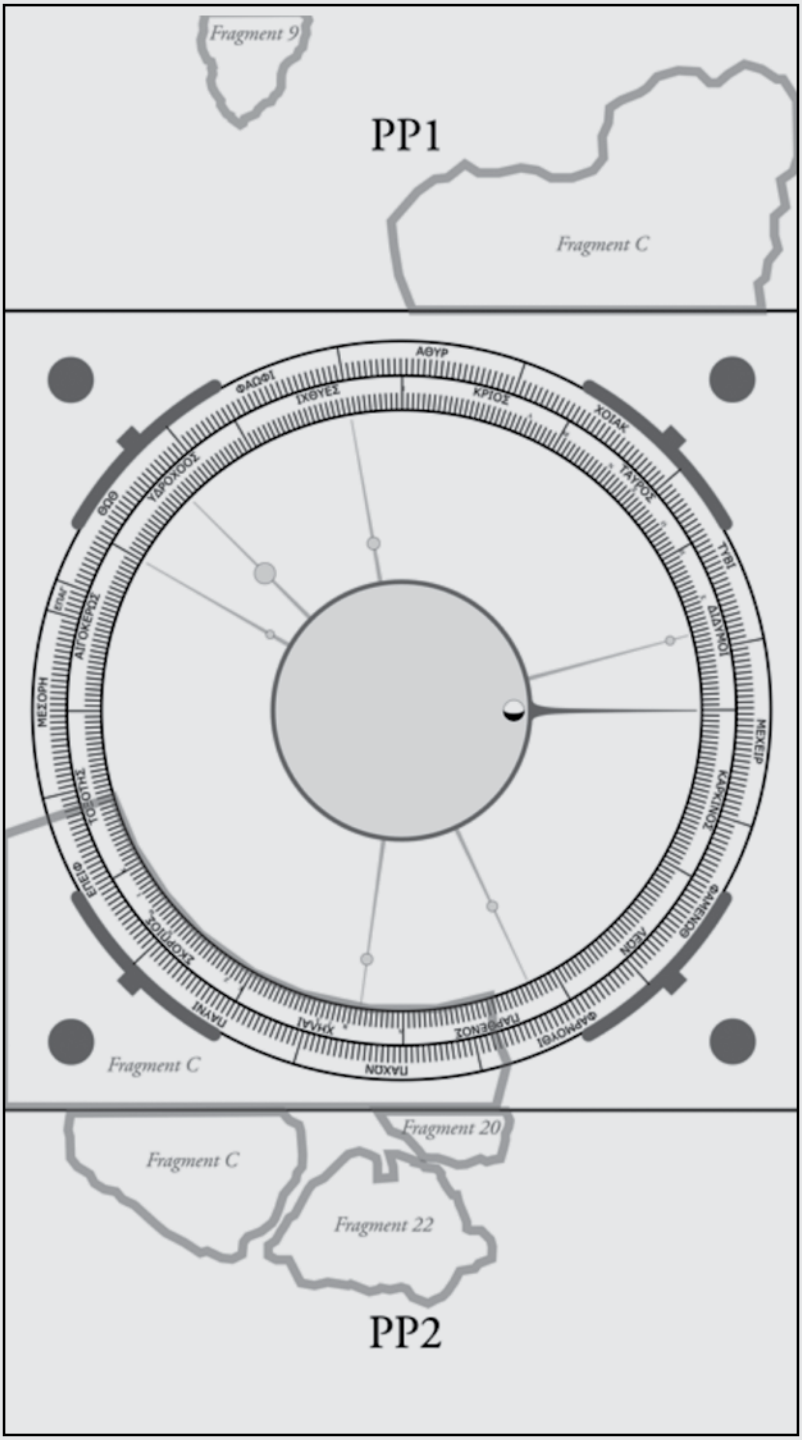

Figure 3.10: *Known original locations of the surviving fragments of the front face*

A satisfying resolution of the index letter sequences has been proposed by T. Freeth, who has portrayed it in a conjectural reconstruction of the Mechanism's front face.[48] The reconstruction can be deduced as follows. One may reasonably assume, first of all, that the sequences of index letters of PP1 col. ii and PP2 col. iv, which begin in the middle of the alphabet, were each continuations of sequences in one of the other pair of columns. It is known that PP2 col. iii began with alpha and included iota, so it cannot have been the first part of the same sequence as PP1 col. ii which also had an event indexed with iota. The alternative is for PP2 col. iii to lead into PP2 col. iv, that is, lettering the events on this plate according to the normal "reading" order for a text in columns, that is, from left to right. One would thus infer that there were no more stellar events listed in col. iii following the event indexed lambda at the 7th degree of Sagittarius. Complementarily, PP1 col. i leads into PP1 col. ii in both the astronomical and the "reading" order, so col. i began with alpha. In each plate of the inscription, one would have seen a single continuous alphabetic sequence, which comprised a complete alphabet in PP2 but an incomplete one in PP1. On the dial, the sequence would have been continuous within each quadrant, but there would have been discontinuities in the sequence of letters at the beginnings of Cancer, Libra, and Capricorn.

Accepting Freeth's hypothesis, we can revisit the reconstruction of PP1 col. i and the questions of how many events it listed and how many lines there were between lines 1-4 in Fragment 9 and line x+1 in Fragment C. Let us consider the possibilities for reconstructing the two columns systematically:

(1) The only lost lines from the top of col. ii were the two that contained the Sun's entry into Aries and the Vernal Equinox, with the index letter iota. In this case, the IA remaining from col. i is in a position intermediate between the original eighth and ninth lines of col. ii, so that the line that ended with the IA must have been either the eighth or the ninth line of col. i.

(1a) If it was the eighth line, it contained the seventh event in the column, and had index letter eta. Then there must have been a ninth line and an eighth event ending the left column, with index theta, to obtain continuity with the right column's index letters.

(1b) If it was the ninth line, it contained the eighth event, had index letter theta, and was the last line and event of col. i.

(2) There were at least three lines, and at least two events, lost from the top of col.

48 Freeth & Jones 2012, Fig. 4; the text of the Parapegma Inscription as shown there reflects a provisional transcription of the fragments and differs in some details from the edition presented here.

ii. Thus the index letter of the top line of col. ii was either theta or a letter earlier in the alphabet than theta. In this case the line of col. i to which the IA belonged would have been at least the ninth line and eighth event of the column, and so would have been indexed with theta or a letter later in the alphabet than theta. Since this overlaps with the lettering of col. ii, we can dismiss this possibility.

Thus we can confirm that col. i had 9 lines and listed 8 events, indexed alpha through theta. On logical grounds we do not have a way of knowing whether the line ending in IA was the eighth line indexed as eta or the ninth line indexed as theta, but the wide line spacing in Fragment 9 argues for this line having been the eighth. PP1 col. ii contained ten (iota through sigma); PP2 col. i contained eleven (alpha through lambda); and PP2 col. ii contained thirteen (mu through omega).

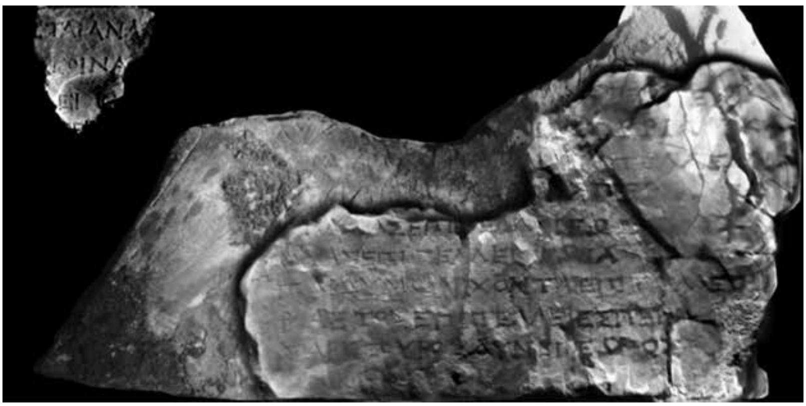

Figure 3.11: *Combined image of PP1, incorporating CT composite images of Fragments 9 (upper left) and C (lower right) superimposed on the 1905 photograph of C (Image: Antikythera Mechanism Research Project)*

We can thus offer a provisional reconstruction of PP1 as follows (Fig. 3.11):

col. i

(9)	1	[Α *v*	Αἰγοκέρως ἄρχ]εται ἀνα[τέλλειν.]	
	2	[*v*	τροπαὶ χει]μ̣εριναί[ί. Α]	
	3	[Β *v*	–7–	ἐπιτέλ]λ̣ει *v* ἐσ̣[πέριος/περία. *nn*]
	4	[Γ *v*	–13–	]̣ Ε̣ [
(lost)	5	[Δ *v*	*lost*	..]
	6	[Ε *v*	*lost*	..]
	7	[Ζ *v*	*lost*	..]
(C)	8	[Η *v*	*lost*	] ΙΑ
(lost)	9	[Θ *v*	*lost*	..]

or

	8	[Η *v*	*lost*	..]
(C)	9	[Θ *v*	*lost*	] ΙΑ

col. ii

(lost)	1	[Ι *v*	Κριὸς ἄρχεται ἐπιτέλλειν.]
	2	[*v*	ἰσημερία ἐαρινή. Α]
(C)	3	[Κ *v*	–12–]̣ Ι ἐσ̣[π]ερ̣[ί]α̣[*nn*]
	4	<u>Λ *v*</u>	<u>Ὑάδ̣</u>[ες δύον]ται ἐσ̣περίαι̣. *v* ΚΑ
	5	<u>Μ *v*</u>	<u>Ταῦρο̣ς̣ ἄ̣ρχ̣ε̣τ</u>αι ἀνατέλλειν. Α
	6	[Ν *v*]	<u>Λύ̣ρα</u> ἐ[πιτ]<u>έ̣λ̣λ̣ε̣</u>[ι] ἑσπερία. *v* ΙΑ
	7	Ξ *v*	Πλειὰς ἐπι[τ]έλλει ἑῷι̣[ο]ς. *v* ΙΖ̣
	8	Ο *v*	Ὑὰς ἐπιτέλλει v ἑώια. *v* Κ̣Ε
	9	Π *v*	Δίδυμοι ἄρχονται ἐπιτέλλει̣ν̣. [Α]
	10	Ρ *v*	Ἀετὸς ἐπιτέλλει ἑσπέριο[ς. *nn*]
	11	Σ *v*	Ἀρκτοῦρος δύνει v ἑῷι̣ος. *v* Ι̣

Two of the missing lines in col. i would have contained the Sun's entries into Aquarius and Pisces.

At this point we have arrived at definitive totals for the events and lines in each column:

PP1 col. i Capricorn – Pisces alpha – theta (five stellar events) 9 lines	PP1 col. ii Aries – Gemini iota – sigma (seven stellar events) 11 lines
PP2 col. iii Libra – Sagittarius alpha – lambda (eight stellar events) 12 lines	PP2 col. iv Cancer – Virgo mu – omega (ten stellar events) 14 lines

3.10 Tentative identifications of missing asterism names

The names of seven asterisms are preserved in the Parapegma Inscription: Sirius, Arcturus, Pleiades, Hyades, Lyra, Aquila, and Orion. As already noted, these are all found among the set of fifteen asterisms that served as a standard repertoire for the majority of parapegmata, starting with the citations of Euktemon and Eudoxos in the Geminos Parapegma and other sources (see section 13). It is a reasonable hypothesis that this repertoire provided all the asterisms of the Parapegma Inscription. Each asterism has four annually recurring visibility events, and in the case of Orion and Scorpius the parapegma tradition also sometimes distinguished between the dates when the asterism begins to rise or set and when its entirety is considered to rise or set, making a total of 68 potential events in a "complete" parapegma. In practice no extant parapegma or set of parapegma data attributed to an individual authority is complete in this sense. The citations of Euktemon in the Geminos Parapegma, for example, amount to only forty events, with another five or so being attested in other sources. Some events seem to have held little interest across the tradition; for example settings of Vindemiatrix and risings of Sagitta are seldom listed. The Mechanism's parapegma, with thirty stellar events, would have been selective even by the tradition's standards.

In several partially preserved lines of the Parapegma Inscription, the name of the asterism is lost but we have some clues to its identity, such as the grammatical number and gender of the name and its approximate length, in addition to the rough date when it was supposed to occur. As a guide to the events that would be plausible candidates for listing within a date range, we have constructed a "model" parapegma (section 13) based on a modern theory for estimating visibility dates. It must be kept in mind, however, that modern visibility models reproduce ancient visibility reports only within very broad tolerances (see section 14); the differences between dates in our model parapegma, for example, and dates of the same events ascribed to Euktemon or Eudoxos exhibit standard deviations of around 10 days. We have also used several other ancient parapegmata and parapegma-like texts as guides to the ranges of dates that the ancient tradition allowed for ancient events.[49]

PP1 col. i

3 [Κύων *v* ἐπιτέλ]λ̣ει *v* ἑσ̣[πέριος. *nn*]
3 [Sirius ri]ses in the eve[ning. *nn*]

The only evening rising that takes place while the Sun is in or near Capricorn is that of Sirius. Sirius's evening rising is surprisingly rarely listed in parapegmata, though the Geminos

49 Most of the texts are conveniently collected in Wachsmuth 1897 and Lehoux 2007.

Parapegma cites Eudoxos for its occurring on the zodiacal date Sagittarius 16, which is about twenty days too early. The available space would suggest a longer asterism name. However, the presence of an otherwise unexplained *vacat* after ἐπιτέλλει might reflect an effort to stretch out a short line of text for better appearance (cf. the *vacat* in the short col. ii line x+6), in which case another *vacat* can be hypothesized after the name.

PP1 col. ii

x+1 [Κ *v* Πλειάδες δύνου]σ̣ι ἑσ̣[π]ερ̣[ί]α̣ [ι. *nn*]
x+1 [Κ *v* Pleiades se]t in the evening. [*nn*]

There is a very strong expectation that a parapegma would list the evening setting of the Pleiades, which would occur while the Sun is in Aries. Moreover, the preserved AI at the left edge requires a plural subject, ruling out other events that fall within this zodiacal month, and the restoration given above fits the available space (estimated 12 letters) well. For alternation between plural and singular forms of the asterism name, compare lines x+2 and x+6.

PP2 col. iii

3 [Β *v* Ἔριφοι ἐπι]τέλλουσιν [ἑ]εσ̣π̣έριοι. ΙΑ
4 [Γ *v* Πλειὰς ἐπιτ]έλλε[ι ἑσ]περία. ΙΔ
5 [Δ *v* Στέφανος ἑῷιος ἐπι]τ̣έλ̣λει. ΙϹ
3 [Β *v* Haedi] rise in the evening. 11
4 [Γ *v* Pleias] rises in the evening. 14
5 [Δ *v* Corona] rises [in the morning]. 16

The surviving text of these lines shows that the listed events for Libra were the evening rising of an asterism with a plural name, probably masculine,[50] then an evening rising of a feminine singular asterism, and thirdly a rising of a singular asterism of indeterminate gender. (Line 5 is the only instance of a stellar event having no indication of morning or evening following the verb; the horizontal spacing relative to the preceding lines

50 It is worth considering the possibility that ἑσπέριος was employed in this line as an adjective of two terminations, modifying a feminine plural asterism. Only two asterisms other than Haedi have plural names among the ones used regularly in parapegmata: the Pleiades and Hyades. Πλειάδες is definitely too long to be squeezed into the available space, which is determined by Χηλαί in line 1. Ὑάδες would fit, but the evening rising of the Hyades (effectively Aldebaran) takes place about twenty days later than the 11th day or degree in Libra; the dates ascribed to Euktemon and Eudoxos are indeed early too in comparison to modern computation, but not *this* early. There is also no credible candidate for a feminine singular asterism having an evening date soon after the evening rising of the Hyades.

suggests that the expected adjective preceded the verb rather than being omitted.) From the day/degree numerals and the Zodiac Dial Scale inscriptions we know that these events fell around the middle of the zodiacal month and that the next stellar event was at Scorpio 4°.

The only masculine plural asterism in the standard Parapegma repertoire is Haedi (ἔριφοι). Our calculations estimate the evening rising of Haedi as occurring while the Sun is in Virgo or (for very southerly latitudes) just entering Libra, but the parapegma tradition inclines to later dates. The Geminos Parapegma states that it falls on Libra day 3 according to Euktemon. Columella (11.2.66) has a listing of the event on September 27, i.e. day 2-4 counted from the Sun's entry into Libra on the autumnal equinox (which he places on the three days September 24-26), and this is consistent with the Euktemon date in the Geminos Parapegma. However, Columella (11.2.73) also lists the same event on October 6, i.e. day 11-13 in Libra. Comparably late dates are given in the Aëtios Parapegma (October 7, ed. Wachsmuth 291), in Lydos, *De Mensibus* (October 6 according to Demokritos, ed. Wünsch 163), and in the Clodius Tuscus Parapegma (October 4, 8, and 9, ed. Wachsmuth 149). We consider the identification of the asterism of line 3 as Haedi to be highly probable.

The feminine name of the asterism of line 4, unless there was a *vacat*, should have been about one letter's width wider than the presumed ἔριφοι of line 3. This was probably Πλειάς, the singular form of the Pleiades attested in PP1 col. ii line x+5. The evening rising of the Pleiades, an event unlikely to be skipped in a parapegma, is listed in the Geminos Parapegma for Libra day 5 according to Euktemon and day 8 according to Eudoxos, both being slightly later than our calculated dates. Closer to line 4's day/degree number 14 are the listings in Pliny (October 10 according to Caesar, 18.74.313), Columella (October 10, 11.2.74), and Clodius Tuscus (October 9 and 12, in addition to several earlier dates, ed. Wachsmuth 146-149).

The event of line 5 occurring at day/degree 16 is most likely the morning rising of Corona Borealis; the date comes too soon after the evening rising of the Pleiades for the evening rising of the Hyades. Again the dates in the Geminos Parapegma are earlier, Libra 7 according to Euktemon and 10 according to Eudoxos. On the other hand, Pliny (18.74.313) gives October 8 specifically for Alphekka according to Caesar and October 15 for the constellation as a whole, Columella (11.2.73-74) gives October 8 and 13-14, and Clodius Tuscus gives October 8, 11, and 13 (along with other earlier dates, ed. Wachsmuth 149).

We know from the Zodiac Dial that there were three stellar events in the zodiacal month of Scorpio, at the 4th, 17th, and 22nd degrees, and two in Sagittarius, at the 3rd and 7th degrees. The corresponding day numbers would have been the same as the degrees in these zodiacal months, or at most differing by one. Since the model parapegma lists well over five stellar events for these signs, any identifications of the events that were listed on the Mechanism would be exceedingly speculative in the absence of further clues.

PP2 col. iv

13 [Ψ *v* Αἶξ ἐπιτέλλει ἑσπερία. ΙΘ]
14 [Ω *v* Ἀρκτοῦρος ἐπιτέλλει ἑῷιος. ΚΑ]
13 [Ψ *v* Capella rises in the evening. 19]
14 [Ω *v* Arcturus rises in the morning. 21]

The morning rising of Arcturus, a few days before the autumnal equinox, was perhaps the single most important and widely recognized stellar event of the year for the Greeks, so that it is hard to believe that the event indexed as omega at the 21st degree of Virgo was anything else. The best candidate for the event indexed psi, at the 19th degree, is the evening rising of Capella.

3.11 Fragment 28

We now turn to the one remaining fragment of the Parapegma Inscription, Fragment 28, that we have not accounted for (Fig. 3.12). Parts towards the ends of five consecutive lines are preserved, but the preserved information is extremely limited:

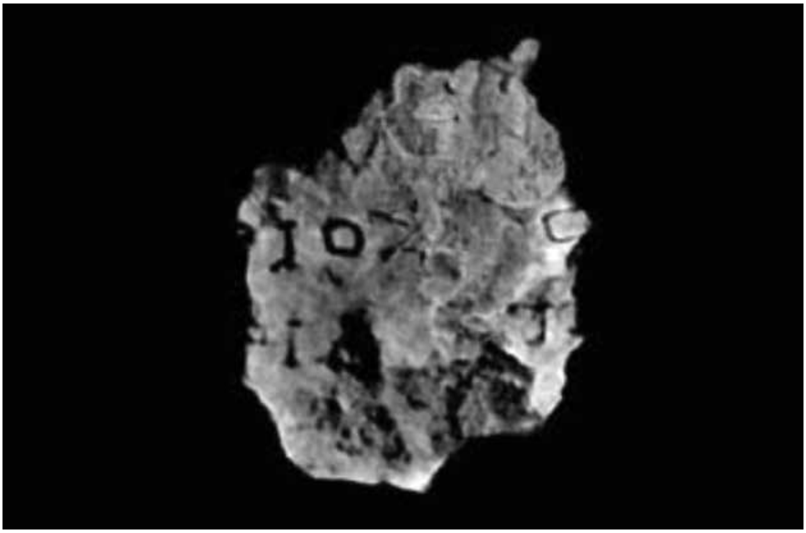

Figure 3.12: *CT composite image of Fragment 28*
(Image: Antikythera Mechanism Research Project)

> line z+1: possibly a stellar event whose numeral indicating the degree or day within the relevant zodiacal sign is in the twenties, but the reading is not certain.
> line z+2: the Sun's entry into a zodiacal sign that does not correspond to a solstice or equinox since the next line is a stellar event.
> line z+3: a stellar appearance or disappearance in the evening, with numeral 16.
> line z+4: appearance or disappearance in the evening of an asterism whose gender is feminine, with numeral in the twenties.
> line z+5: indeterminate because of severe surface damage.

This fragment obviously did not come from anywhere in PP1 col. ii, and the zodiacal sign entered in line z+2 cannot be Capricorn, Cancer, or Libra. We can also rule out Scorpio and Sagittarius in the latter column, because the day/degree numerals preserved in Fragment 28 lines z+3 and z+4 do not even nearly match the preserved locations of the first two index letters in the Scorpio and Sagittarius sectors of the Zodiac Dial Scale.

There was at most one line below PP1 col. i line x+1, so if Fragment 28 was part of this column, it must have been partly or entirely above line x+1. Moreover, the Sun's entry into Pisces would have had to come between Fragment 28 line z+4 and col. i line x+1, since the day/degree number 11 in col. i line x+1 is less than the day/degree numbers in Fragment 28 lines z+3 and z+4. Thus the only possible placement for Fragment 28 in PP1 col. i would be such that Fragment 28 line z+2 is the Sun's entry into Aquarius.

We have thus narrowed down the possible identifications of the zodiacal sign entered in line z+2 to Aquarius, Leo, or Virgo. The listed events immediately following this entry were two evening risings or settings, the second of which was of a feminine singular asterism. No feminine asterism has an evening event during or sufficiently near the zodiacal month of Leo, so we are left with Aquarius and Virgo.

For Aquarius, the only candidate for the feminine asterism is Lyra. Our calculations place Lyra's evening setting late in the zodiacal month of Capricorn or early in that of Aquarius. In the Geminos Parapegma it falls on Aquarius day 3 according to Euktemon and day 11 according to Eudoxos; other parapegmatic sources give a wide range of dates, among which the latest are February 6 (approximately Aquarius 16) in Clodius Tuscus (ed. Wachsmuth 122) and February 7 (approximately Aquarius 17) in Pliny (*Naturalis Historia* 18.235, ed. Wachsmuth 324). The necessary restoration, Λύρα δύεται, at ten letters is very short for the estimated 14-letter gap (the somewhat more common verb δύνει would make it still shorter). There also exists one just acceptable candidate for the event of line z+3: the evening setting of Delphinus. By our calculations, this should have occurred around the middle of Capricorn, while in the Geminos Parapegma it falls on Capricorn day 27 according to Euktemon, and Aquarius day 4 according to Eudoxos; the latest date given in the parapegma literature seems to be January 28 (approximately Aquarius 7) in the Aëtios Parapegma (ed. Wachsmuth 293).

Since PP1 col. i contained a total of five stellar events, including one in Capricorn on line 3 and one in Pisces on line x+1, with the two events on z+3 and z+4 hypothetically assigned to Aquarius, the remaining event could have belonged to Capricorn on line 4, Aquarius on line z+5, or Pisces on line x+0 or x+2, so that we could not assign absolute line numbers to the lines of Fragment 28 or to x+1 on Fragment C. The proposed restoration of Fragment 28 would be as follows:

(28) z+1 [̣ *v*] Κ̣[*n*?]
z+2 [̣ *v* Ὑδροχόος ἄρχεται ἐπιτ]έ̣λλειν. [Α]
z+3 [̣ *v* Δελφὶς δύεται ἑσπέ]ριος. *v* Ι̣C
z+4 [̣ *v* Λύρα δύεται ἑσπε]ρία̣. *v* Κ[*n*?]
z+5 [–*n*+11–]Ε̣ ̣ ̣[ ]

(28) z+1 [ ] 2[*n*?]
z+2 [Aquarius begins] to rise. [1]
z+3 [Delphinus sets] in the evening. 16
z+4 [Lyra sets] in the evening. 2[*n*?]
z+5 [ ] ... [ ]

We now turn to Virgo. In this sign, Capella is the only possibility for the feminine asterism in line z+4. Our calculations estimate that its evening rising could fall anywhere within the zodiacal month of Virgo, with the date varying considerably according to latitude. In the Geminos Parapegma it falls on Virgo day 20 according to Euktemon, and Libra day 4 according to Eudoxos. The restoration Αἶξ ἐπιτέλλει, at 12 letters, would need a bit of stretching to fit the 14-letter gap, but this could have been done with small *vacats* or just slightly wider letter spacing, or line z+2 might have been more tightly spaced than usual.

An evening event that could plausibly have preceded the evening rising of Capella in Virgo's zodiacal month is the evening setting of Vindemiatrix. By our calculations this would occur within a few days of the 12th day of Virgo. But the restoration Προτρυγητὴρ δύνει (or still worse, δύεται) seems too long for the space, unless the rare variant Τρυγητήρ or Τρυγητής was used. Moreover, it would be unexpected to have Vindemiatrix represented in the parapegma by its evening setting rather than its morning rising, a few days later, which was traditionally the harbinger of the vintage as the star's Greek and Latin names signify; the only attestation of the evening setting in the parapegma literature seems to be in the Geminos Parapegma, Leo day 18 according to Dositheos, a surprisingly early date.

The only other stellar event we can suggest for z+3 is the evening rising of Pegasus; Ἵππος ἐπιτέλλει is a good fit to the available space. The model parapegma, which in general appears to yield dates for this large constellation that are not as close as one would wish to the dates in ancient parapegmata, predicts dates for the evening rising late in the zodiacal month of Cancer or early in that of Leo, and the Geminos parapegma cites Euktemon for Leo day 17.[51] On the other hand, the two dates offered by the Clodius Tuscus Parapegma (ed. Wachsmuth 145-146) are September 6 (approximately Virgo 11) and 14 (approximately Virgo 19), both comfortably within the zodiacal month of Virgo, and Lydos *De Mensibus* (ed. Wünsch 160) also gives September 6 with Eudoxos as authority. (This event is not among the Eudoxos data in the Geminos Parapegma.)

On the zodiac dial, stellar events are marked at the 19th and 21st degrees of Virgo. These cannot be reconciled with the day/degree numerals in lines z+3 and z+4 unless these numerals are to be interpreted as day numbers counted from the Sun's entry into the zodiacal sign, and in this case the zodiacal month of Virgo would have had to be assumed to be 31 days long rather than 30 (its length according to the Geminos Parapegma). The restoration would thus be as follows:

51 Pliny 18.74.309 gives August 12 according to "the Athenians," which would closely match the Euktemon date.

(28) 10 [Υ *v*] Ḳ [n?]

11 [Φ *v* Παρθένος ἄρχεται ἐπιτ]ẹ́λλειν. [Α]

12 [Χ *v* Ἵππος ἐπιτέλλει ἑσπέ]ριος. *v* Ị̣C

13 [Ψ *v* Αἶξ ἐπιτέλλει ἑσπε]ρίạ . *v* Κ

14 [Ω *v* Ἀρκτοῦρος ἐπιτέλλει] ẹ̓ ῷ̣ ị [ος. ΚΒ]

(28) 10 [Υ *v*] 2[*n*?]

11 [Φ *v* Virgo begins] to rise. [1]

12 [Χ *v* Pegasus rises] in the evening. *n* 16

13 [Ψ *v* Capella rises] in the evening. *n* 20

14 [Ω *v* Arcturus rises] in the morning. [22]

3.12 Astronomical assessment

A recent astronomical assessment of the Parapegma Inscription was based on the contents in PP1 col. ii as transcribed by Rehm and Price-Stamires, that is, lines x+2 through x+9 without knowledge of the degree/date numerals.[52] In other words, the only available information was the order of six stellar phenomena relative to each other and to the two preserved dates of sign entry. For purposes of analysis, the authors computed dates of the stellar phenomena by modern theory for 150 BC and for a range of latitudes from 25° to 45°, making almost identical assumptions to ours about which stars constitute each asterism for purposes of visibility, but applying a different model for stellar visibility.[53] For any pair of stellar events listed as occurring consecutively in the Parapegma Inscription, a "sequence error" was defined as 0 if the order of events agreed with modern computation for a given latitude, and otherwise as the positive number of days separating dates of the two events as computed by the modern visibility model. "Zodiac errors" were similarly computed between all the stellar events and the dates of sign entry. The sum of sequence errors or of zodiac errors for a particular latitude was taken as a measure of the fit of the Parapegma Inscription's contents to that latitude.

The conclusion of this study was that the contents of PP1 col. ii lines x+2 to x+9 fit best latitudes between 33.3° and 37.0°. Similar tests of sequence and zodiac errors applied to the Euktemon and Eudoxos data in the Geminos Parapegma found larger inaccuracies than for the Mechanism data, especially in the case of the Eudoxos data which includes several large outliers that strongly affect the calculated errors.

The discovery of the date/degree numbers in the Parapegma Inscription offers an opportunity for a more precise assessment of the recorded phenomena. Complete numerals are preserved for five stellar events in PP1 col. ii in the zodiacal months Aries, Taurus, and Gemini, in all of which the identity of the asterism and phenomenon is certain. A further three numerals of events in Libra are preserved in PP2 col. i, and we consider our restorations of the lost asterism names to be probable enough to use these events since the descriptions of the events are otherwise at least partly preserved. The identifications of the eight asterisms and phenomena whose degree numbers in Virgo, Scorpio, and Sagittarius are marked by index letters on the zodiac dial seem to us to be too uncertain to use. We thus have taken into consideration a smaller data set consisting of just the five events in PP1 col. ii, and a larger set that also includes the three events in PP2 col. i.

52 Anastasiou et al. 2013.

53 See Appendix 1 (section 13) for our identifications of asterisms with individual stars; the only divergence is that Anastasiou *et al.* use an aggregate apparent magnitude and mean position for the Pleiades. The visibility models are discussed in Appendix 2 (section 14).

Zodiacal dates for each asterism were calculated by modern theory for 100 BC by the method described in Appendix 2. The degree/date numbers of the Mechanism's inscription and the degree numbers associated with the Scorpio events were treated as zodiacal dates, using the lengths of zodiacal months in the Geminos Parapegma. In the following table, we give the latitude yielding the closest fit to the Mechanism data (as defined in Appendix 2), the mean difference (Mechanism minus modern theory), and standard deviation. Fig. 3.13 shows how the standard deviation varies with the latitude used for the modern theory calculations.

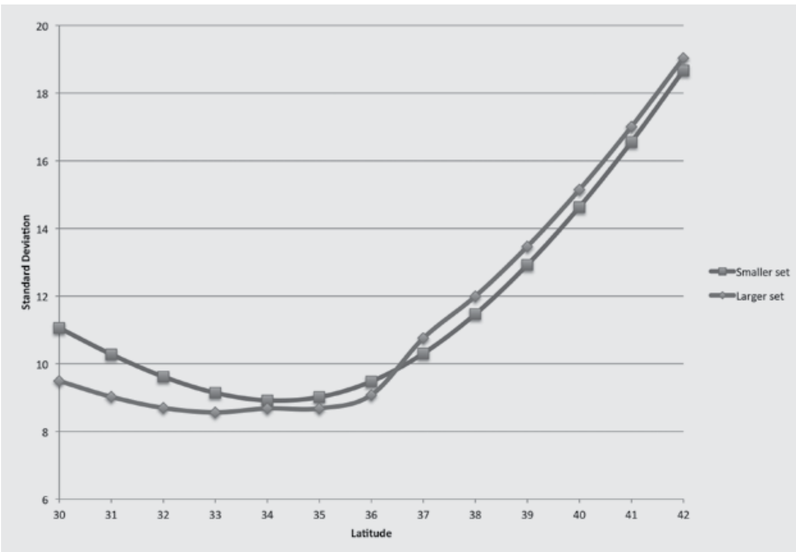

Figure 3.13:. *Fit of the Parapegma Inscription data to modern theory calculations according to latitude*

	Latitude	Mean difference	Standard deviation	Number of events
Smaller set	34° 13′	–3.1 d	8.9 d	5
Larger set	33° 4′	–0.6 d	8.6 d	8

The results are broadly consistent among the data sets and consistent with the results obtained by Anastasiou *et al.* In Appendix 2 we show indications that best fits to our visibility model may underestimate latitudes by about a degree and a half. Correcting for this would bring the estimated latitude for the data in the Parapegma Inscription to about 35°, which suggests that its contents were based, directly or indirectly, on observations made at a mid-Mediterranean locality such as Rhodes or, at furthest north, southern Greece. Egypt (roughly 31° or less) is much less likely, and Epirus (around 41°) more or less out of the question. The small mean difference found for the larger set could mean either that the inscription was based on recent observations or that, in adapting older data, the stellar phenomena were aligned with zodiacal dates in a manner that would conceal the precessional shift. The standard deviations for the best fit latitudes are in the same range as we have found for the Euktemon and Eudoxos data in the Geminos Parapegma; the number of dates preserved in the Parapegma Inscription is too small to allow a meaningful appraisal of whether its dates are on the whole more or less accurate than the Euktemon and Eudoxos dates.

3.13 Appendix 1. Model Parapegma

The fifteen asterisms for which the parapegma tradition transmits statements of risings and settings attributed to Euktemon are as follows:

Greek name	*Translation*	*Modern name*
Ἀετός	Eagle	Aquila
Αἴξ	Goat	Capella
Ἀρκτοῦρος	Bear-guard	Arcturus
Δελφίς	Dolphin	Delphinus
Ἔριφοι	Kids	Haedi
Ἵππος	Horse	Pegasus
Κύων	Dog	Sirius
Λύρα	Lyre	Lyra
Ὀϊστός	Arrow	Sagitta
Πλειάδες, Πλειάς	Pleiades, Pleiad	Pleiades
Προτρυγητήρ	Vintage-bringer	Vindemiatrix
Σκορπίος	Scorpion	Scorpius
Στέφανος	Crown	Corona Borealis
Ὑάδες, Ὑάς	Hyades, Hyad	Hyades
Ὠρίων	Orion	Orion

The majority of subsequent authorities and texts in the ancient parapegma tradition used these asterisms either exclusively or with very few additions. The parapegma presented in this appendix gives zodiacal day numbers for all four visibility events for the asterisms of Euktemon, computed by the software Alcyone Planetary, Lunar and Stellar Visibility version 3.1.0 (PLSV), which employs an implementation of the "classical" visibility model of Schoch (see Appendix 2). Julian calendar dates of the events were determined for 100 BC and for three latitudes: 31° (approximately valid e.g. for Lower Egypt and Alexandria), 36° (e.g. Rhodes and generally mid-Mediterranean latitudes), and 41° (e.g. Epirus and Rome). For individual stars Sirius (α CMa), Arcturus (α Boo), Capella (α Aur), and Vindemiatrix (ε Vir), the visibility dates can be determined directly. For the other asterisms, the following criteria were adopted:

- Small constellations and clusters (Lyra, Aquila, Corona Borealis, Pleiades, Hyades, Haedi, Sagitta, Delphinus): the asterism is considered to rise or set (in the sense of Parapegma phenomena) when its brightest star rises or sets.
  - Pleiades: Alcyone (η Tau)
  - Hyades: Aldebaran (α Tau)[54]
  - Lyra: Vega (α Lyr)
  - Aquila: Altair (α Aql)

- Corona Borealis: Alphekka (α CrB)
- Haedi: η Aur
- Delphinus: Rotanev (β Del)
- Sagitta: γ Sge[55]

- Large constellations (Orion, Scorpius, Pegasus): the asterism is considered to begin to rise or set when the first of certain designated bright stars rise or set, and it is considered to rise or set entire when all the designated stars have risen or set.
  - Orion (large constellation): Rigel (β Ori), Betelgeuse (α Ori), Bellatrix (γ Ori), Saiph (κ Ori)
  - Scorpius: Acrab (β Sco), Shaula (λ Sco)
  - Pegasus: Scheat (β Peg), Markab (α Peg), Algenib (γ Peg), and Alpheratz (α And)[56]

54 Aldebaran was considered by Greek astronomers to be part of the Hyades; see e.g. Ptolemy, *Almagest* 7.5, ed. Heiberg 2.88.

55 Sagitta, a small constellation consisting of only dim stars, is problematic in the parapegma tradition. Only setting dates for Sagitta were recorded (Columella 11.2.21 assigns its evening rising to February 22, but this is obviously an error for the evening setting), and in most sources the dates are extremely late. The evening setting, according to the PLSV model, should take place in early January (January 2 for latitude 31°, January 10 for 41° in 100 BC). However, the date attributed to Euktemon in the Geminos Parapegma (the constellation's name is missing in the Greek text, but can be restored from the medieval Latin version) was the 22nd of the zodiacal month of Aquarius, which would be about the middle of February, and other parapegma statements in Columella (11.2.21, making the correction just mentioned) and the Aëtios Parapegma (ed. Wachsmuth 293) and Clodius Tuscus Parapegma (three dates, ed. Wachsmuth 123-124) have dates in the range February 18-27. These greatly outnumber the attestations of dates close to the expected ones in the Clodius Tuscus Parapegma (January 13, ed. Wachsmuth 119), and Pliny 18.64.234 (January 5 specifically for Egypt). The PLSV model predicts Sagitta's morning setting in mid August (August 8 for 31°, August 18 for 41° in 100 BC). The Euktemon date in the Geminos Parapegma is the 10th day in Virgo, about September 5, which is Pliny's date for Attica (18.74.310), while the Quintilius Parapegma (ed. Wachsmuth 294), Pliny again (for Assyria, 18.74.309), the Aëtios Parapegma (ed. Wachsmuth 291), and the Clodius Tuscus Parapegma (ed. Wachsmuth 145) have dates ranging from August 25 to September 4. Anastasiou *et al.* 2013, A8 (online version only) explain the discrepancy between the Euktemon dates for Sagitta and those predicted by their visibility model as due to the dimness of γ Sge; but this will not do for the huge lag of the attested dates for evening setting after the expected dates since by the attested dates the constellation is well below the ideal horizon at sunset.

56 Alpheratz was considered to be common to Andromeda and Pegasus; see Ptolemy, *Almagest*, 7.5, ed. Heiberg 2.76. Pegasus is a very large constellation, making the identification

The Julian calendar dates were then converted to zodiacal day numbers using the dates of the Sun's entry into the zodiacal signs computed for 100 BC by the JPL Horizons ephemeris.[57]

Even for individual stars, modern models of stellar visibility are based on a slender empirical base, and one should assume that our computed zodiacal dates are only rough approximations of the dates when the risings and settings would have been observed by an ancient observer with reasonably good eyesight, a clear horizon, and favorable atmospheric conditions. Closely spaced groups of stars would probably have had a greater effective visibility than the brightest single star among them; in particular, our model surely underestimates the visibility of the Pleiades (apparent magnitude 1.6 in contrast to Alcyone's magnitude of 2.9). For the larger constellations, we have the added uncertainty concerning which stars any particular parapegmatist would have considered essential for stating that the constellation was partially or completely visible.

We have also given stellar dates attributed to Euktemon and Eudoxos in the Geminos Parapegma, supplemented for Euktemon by a few dates that can be estimated by combining information from the Geminos parapegma with the parapegma in the manuscript *Vind. phil. gr.* 108 ff. 282v-283r (V) and the Miletos parapegma fragment IMilet. inv. 456A (M).[58] For a comparison of these dates with the those generated by the PLSV model, see Appendix 2.

of the "essential stars" particularly difficult; we have selected the four brightest stars, which form the quadrangle that represented the horse's torso.

57 http://ssd.jpl.nasa.gov. We used tropical longitudes since that is ostensibly the frame of reference of parapegmata that count days from a solstice or equinox.

58 The Vienna text, which gives unattributed intervals in days between consecutive stellar risings and settings rather than absolute day numbers in a chronological framework, is edited in Rehm 1913, 14-26; for its close relation to the Euktemon data in the Geminos Parapegma see pp. 12-13 and Hannah 2002. IMilet. inv. 456A was originally published in Diels & Rehm 1904, with a more cautious reedition in Lehoux 2005. (The dates of stellar phenomena given as applicable to Attica in Pliny 18 are also mostly equivalents of Euktemon dates expressed in the Roman calendar.) The intervals between stellar phenomena reported for Euktemon in the various sources exhibit frequent small variations (and occasional larger ones), probably because Euktemon's dates were adapted in different ways to the zodiacal frameworks of later parapegmata.

ASTERISM	***EVENT***	***31°***	***36°***	***41°***	***EUKTEMON***	***EUDOXOS***
Pleiades	ES	♈ 17	♈ 17	♈ 17	♈ 10	♈ 13
Scorpius begins	ER	♈ 21	♈ 21	♈ 20	♓ 29[59]	
Orion begins	ES	♈ 29	♈ 26	♈ 23		♈ 13
Hyades	ES	♈ 28	♈ 27	♈ 26	♈ 23	♈ 21
Lyra	ER	♉ 5	♈ 28	♈ 19	♉ 2	♈ 27
Capella	MR	♉ 6	♈ 28	♈ 15	♉ 8	♉ 9
Vindemiatrix	MS	♈ 29	♉ 7	♉ 20		♈ 13
Orion	ES	♉ 13	♉ 11	♉ 8	V: ?[60]	♉ 1
Sirius	ES	♉ 20	♉ 14	♉ 11	♉ 2	♉ 2
Haedi	ES	♉ 12	♉ 14	♉ 16		
Haedi	MR	♉ 21	♉ 18	♉ 14		
Scorpius	ER	♉ 19	♉ 20	♉ 22		
Sagitta	ER	♉ 30	♉ 24	♉ 19		
Pleiades	MR	♉ 22	♉ 25	♉ 29	♉ 13	♉ 22
Capella	ES	♉ 22	♉ 26	♉ 30	VM: ♉ 27[61]	
Scorpius begins	MS	♉ 28	♉ 27	♉ 25		♉ 11
Aquila	ER	♊ 3	♉ 31	♉ 26	♉ 31	♊ 7
Scorpius	MS	♉ 29	♉ 31	♊ 4		♉ 21
Delphinus	ER	♊ 8	♊ 3	♉ 30		♊ 18
Arcturus	MS	♉ 31	♊ 9	♊ 22	♉ 32	♊ 13
Hyades	MR	♊ 5	♊ 9	♊ 14	♉ 32	♊ 5
Orion begins	MR	♊ 27	♋ 1	♋ 7	♊ 24[62]	♊ 24
Corona	MS	♊ 31	♋ 10	♋ 21		♌10[63]
Orion	MR	♋ 14	♋ 19	♋ 26	♋ 13	♋ 11
Pegasus	ER	♌ 3	♋ 28	♋ 21	♌ 17	
Sirius	MR	♋ 23	♋ 30	♌ 3	♋ 27[64]	♋ 27
Aquila	MS	♌ 1	♌ 5	♌ 9	♋ 28	♌ 5
Sagitta	MS	♌ 13	♌ 18	♌ 23	♍ 10	
Lyra	MS	♌ 13	♌ 21	♌ 30	♌ 17	♌ 22
Delphinus	MS	♌ 17	♌ 21	♌ 25		♌ 18
Vindemiatrix	ES	♍ 10	♍ 12	♍ 14		
Capella	ER	♍ 30	♍ 17	♌ 28	♍ 20	♎ 4
Haedi	ER	♎ 1	♍ 21	♍ 5	♎ 3	
Vindemiatrix	MR	♍ 24	♍ 22	♍ 21	♍ 10	

ASTERISM	EVENT	31°	36°	41°	EUKTEMON	EUDOXOS
Arcturus	MR	♎ 1	♍ 28	♍ 25	♍ 10[65]	♍ 19
Pleiades	ER	♎ 3	♍ 30	♍ 24	♎ 5	♎ 8
Pegasus	MS	♎ 1	♎ 4	♎ 7		
Scorpius begins	ES	♎ 12	♎ 9	♍ 29		♎ 12
Scorpius	ES	♎ 17	♎ 10	♎ 5		♎ 17
Corona	MR	♎ 19	♎ 14	♎ 9	♎ 7	♎ 10[66]
Hyades	ER	♏ 1	♎ 29	♎ 28	V: ♎ 20[67]	♎ 22
Arcturus	ES	♎ 27	♏ 6	♏ 15	♏ 5	♏ 8
Pleiades	MS	♏ 15	♏ 16	♏ 17	♏ 15	♏ 19
Orion begins	MS	♏ 20	♏ 17	♏ 15	♏ 15	♏ 19
Lyra	MR	♏ 26	♏ 19	♏ 11	♏ 10	♏ 21
Scorpius begins	MR	♏ 19	♏ 19	♏ 19		♏ 18
Hyades	MS	♏ 21	♏ 20	♏ 20	♏ 27	♏ 29
Orion begins	ER	♏ 22	♏ 24	♏ 26		♏ 12
Sirius	MS	♐ 7	♏ 31	♏ 29	♐ 7	♐ 12
Corona	ES	♏ 25	♐ 3	♐ 12		♑ 9[68]
Orion	MS	♐ 5	♐ 4	♐ 2	V: ?[69]	♐ 8
Orion	ER	♐ 10	♐ 14	♐ 18		
Haedi	MS	♐ 11	♐ 14	♐ 19		
Scorpius	MR	♐ 14	♐ 17	♐ 20	♐ 10[70]	♐ 21
Capella	MS	♐ 13	♐ 18	♐ 24	♐ 19	♐ 23
Aquila	MR	♐ 28	♐ 25	♐ 22	♐ 15	♐ 26
Sagitta	MR	♑ 1	♐ 27	♐ 23		
Sirius	ER	♑ 3	♑ 8	♑ 11		♐ 16
Aquila	ES	♑ 5	♑ 8	♑ 11	♑ 7	♑ 18[71]
Delphinus	MR	♑ 13	♑ 10	♑ 7	♑ 2	♑ 12[72]
Sagitta	ES	♑ 10	♑ 14	♑ 18	♒ 25[73]	
Delphinus	ES	♑ 14	♑ 16	♑ 19	♑ 27	♒ 4
Lyra	ES	♑ 19	♑ 27	♒ 5	♒ 3	♒ 11
Vindemiatrix	ER	♒ 24	♒ 22	♒ 20	♓ 12	
Arcturus	ER	♓ 10	♓ 6	♓ 2	♓ 12	♓ 4
Pegasus	ES	♓ 5	♓ 7	♓ 10	V: ♒ 25[74]	
Pegasus	MR	♓ 17	♓ 17	♓ 17	♓ 14	
Corona	ER	♓ 23	♓ 17	♓ 11		♓ 21

59 "The first stars of Scorpius set."

60 In V the evening rising of Orion is listed after the evening setting of the Hyades but as 14 days before the evening setting of Sirius, which is only 10 days after the evening setting of the Hyades. The numeral must be corrupt.

61 IMilet. inv. 456A col. ii lists for what are probably the last seven days of Taurus the following events: (1) an evening event according to Euktemon; (2) no event; (3) the evening setting of Capella according to an authority whose name is lost, Philippos, and the Egyptians; (4) the evening setting of Capella according to Kalaneus of the Indians; (5) no event; (6) the evening rising of Aquila according to Euktemon, (7) the morning setting of Arcturus according to Euktemon and the evening rising of Aquila according to Philippos. V lists the "setting of Capricorn" following 18 days after the morning rising of the Pleiades and five days before the evening rising of Aquila. Αἰγόκερω ("of Capricorn") must be a corruption of Αἰγός ("of Capella"). The Geminos Parapegma has, for Taurus day 25, "Aquila (Ἀετός) sets in the evening," which is manifestly an error, and Manitius plausibly conjectured that the constellation name here was again a corruption of Capella (Αἴξ).

62 "Orion's shoulder rises."

63 This date is clearly an error, though a statement in the Clodius Tuscus Parapegma (ed. Wachsmuth 142) that the setting takes place on August 5, which would be approximately the same date as Leo day 10, shows that it was present in the tradition at an early date.

64 A second entry at ♌ 3: "Sirius conspicuous."

65 A second entry at ♍ 20: "Arcturus conspicuous."

66 Constellation name restored by Manitius.

67 "From rising of Corona to rising of Hyades, 13 days. From rising of Hyades to setting of Arcturus, 16 days."

68 Like the Eudoxos date of Corona's morning setting, this is clearly an error, though the Clodius Tuscus Parapegma (ed. Wachsmuth 117) and Lydos, *De Mensibus* (ed. Wünsch 73) give an approximately equivalent date, January 1.

69 "From setting of Pleiades to setting of Orion entire, 3 days." This would put the rising of Orion at about ♏ 15, which is implausibly early. The next event listed in V is the morning setting ofSirius, so the date for Orion's morning setting should be before ♐ 7.

70 "The sting of Scorpius rises."

71 Names of Eudoxos and constellation restored by Manitius.

73 Constellation name restored by Wachsmuth on the basis of the Latin version. Manitius conjectures Pegasus. V gives both the setting of Sagitta and the *rising* of Pegasus on the same day, while it has the *setting* of Pegasus 16 days later and 12 days before the vernal equinox ("From setting of Sagitta and rising of Pegasus to <rising> of Vindemiatrix and Arcturus and setting of Pegasus, 16 days"). Obviously the two events for Pegasus have been erroneously interchanged. Note that the Geminos parapegma puts Euktemon's date for the evening rising of Pegasus two days after the evening risings of Vindemiatrix and Arcturus.

74 See preceding note.

3.14 Appendix 2. Modelling stellar visibility phenomena

Whether or not a star is visible close to the time when it crosses the horizon at rising or setting depends on astronomical, geographical, atmospheric, and meteorological conditions in addition to the visual acuity, sensitivity, and observational experience of the individual observer. If the visibility of a constellation is in question, one must also take into account which star or set of stars are considered to constitute the constellation's essential parts.

The astronomical factors are reducible to the star's apparent magnitude and the apparent positions of the star and the Sun relative to the horizon. These can be modelled accurately for a particular latitude and chronological period by modern theory, except that we are unlikely to know the outline of an ancient observer's horizon. Hence we can determine the exact dates when a star crosses the eastern or western *ideal* horizon simultaneously with the Sun. It is not possible, however, to model with exactitude the number of days after an ideal morning rising or setting a star will have be visible or be seen setting for the first time by a typical observer, or how many days before an ideal evening setting or rising a star will be visible or be seen rising for the last time, and there does not even exist a satisfactory body of empirical data on the basis of which one could say how accurate the existing visibility models are.

According to the classical "*arcus visionis*" approach to modelling visibility of heavenly bodies, which goes back to Ptolemy, the primary criterion for visibility is whether the difference in altitude (or depression) between the apparent positions of the body and the Sun is greater than a certain arc (the *arcus visionis*) which is dependent on both the magnitude of the body and the difference in azimuth between its rising or setting points and those of the Sun around the date of the visibility phenomenon.[75] In general, the larger the *arcus visionis,* the further the date of the visibility phenomenon is from the ideal phenomenon. The azimuthal factor can be treated in a simplified way, by assigning to a given stellar magnitude two arcus visionis values, one of which applies to the phenomena in which the Sun and star are both rising or both setting (i.e. morning rising and evening setting), while a smaller value applies to the phenomena in which one body rises while the other sets (evening rising and morning setting). Alternatively, one can attempt to model a vari-

75 In the simplest form, the test is applied to the moment when the apparent altitude of the body is zero. However, the outline of the true horizon can advance or delay the moment of sunrise or sunset relative to the rising or setting of the body; and moreover because of atmospheric extinction it is unlikely that a star will be visible right at the horizon. These effects can be compensated by setting a "critical altitude" that the body must exceed in order to be visible.

able arcus visionis dependent on both the azimuth difference and the magnitude; such a model ought to provide a better representation of the visibility conditions for stars that are not close to the ecliptic. In any case, values for *arcus visionis* should be empirically calibrated, but there is a dearth of reliable data for doing this.[76]

An alternative approach, developed by Anastasiou *et al.,* seeks to determine criteria for stellar visibility from "first principles".[77] They first model the brightness of an arbitrary point of the sky as a function of the point's altitude, the Sun's depression below the horizon, and the azimuthal distance between the point and the Sun, on the basis of empirical measurements published by Nawar and by Koomen et al.[78] This is then combined with Tousey and Koomen's table estimating the minimum magnitude for a star to have a 98% probability of visibility as a function of the brightness of the immediately surrounding sky.[79]

For the present paper we have used the Alcyone Software freeware program Planetary, Lunar, and Stellar Visibility version 3.1.0 (henceforth PLSV). This program uses an *arcus visionis* model for stellar visibility, with *arcus visionis* (h) determined as a function of apparent magnitude ($\boldsymbol{m}$) according to the following default relations derived by Swerdlow and Lange from Schoch's estimates *of arcus visionis* for the superior planets:[80]

$$h_{\mathrm{MR,ES}} = 10.5° + 1.4°m$$

$$h_{\mathrm{MS,ER}} = 8.9° + 1.1°m$$

The critical altitude for visibility was set at 0°, that is, it was assumed that in the absence of solar glare a star would be visible when at the altitude of the (ideal) horizon. A zero critical altitude is certainly not correct, and the *arcus visionis* relations depend on empirical data of uncertain quality. Although the software allows these parameters to be modified, we have retained the defaults since we do not have a basis for determining more appropriate values. For the principal stars used in ancient parapegmata, the values of *arcus visionis* yielded by the formulas given above fall in the range of 7°-16°.

Anastasiou *et al.* report dates of six phenomena involving four individual stars and the

76 See the discussion of these problems (by N. M. Swerdlow and R. Lange) "Sources of Computations and Cautions concerning Accuracy" at http://www.alcyone.de/plsv/documentation/index.html.

77 Anastasiou et al. 2013, A1-A4 (in the online version).

78 Nawar 1983; Koomen et al. 1952.

79 Tousey & Koomen 1953.

80 Schoch 1927.

Pleiades, computed by their method for 150 BC and for a range of latitudes, from which we have selected those for latitudes 31°, 36° and 41°, and in addition two further phenomena of Vega computed for the same year and the latitude of Athens.[81] The mean difference of their dates over those we compute for the same year and latitude by means of PLSV is approximately +1.5 days, with a standard deviation of approximately 3.8 days. While the number of dates compared is not sufficient to obtain a precise measure of how closely the two methods agree, let alone to diagnose their divergences, the agreement validates the usefulness of either method as a provisional standard for evaluating ancient parapegmata.

For Mediterranean latitudes the daily change in the altitude difference between the Sun and a star can be as little as around half a degree per day or as great as nearly a degree per day. If we suppose that two observers in the same period and locality are not likely to have reported a visibility phenomenon for the same star on dates having the altitudinal difference between star and Sun varying by more than say 5° between the two observations, we can conclude that discrepancies larger than ten days between dates in the ancient sources cannot be explained entirely in terms of visual acuity, local atmospheric conditions, or the defectiveness of the modern visibility model. We may hope by a similar argument that PLSV will not normally yield dates for the risings and settings of an individual star differing by more than ten days from the dates when a competent ancient observer would report the same events, presuming that the modern model is applied to the correct star, latitude, and chronological period.

Precession, and to a lesser degree, stellar proper motion, lead to changes in the dates of visibility phenomena relative to each other and to the solstices and equinoxes, but over the three or four centuries from the beginnings of the parapegma tradition to the date of the Mechanism's manufacture these changes are small. In the three centuries between 400 BC and 100 BC, the dates of stellar phenomena should shift on average about 1.8 days later in the Julian calendar, and about 4.2 days later relative to the solstices and equinoxes, with a standard deviation of a little over one day in either case, so that the relative dates of the phenomena are fairly stable.[82] From a sufficiently large body of zodiacal dates of

81 The dates computed for Aldebaran ES and MR, Vega ER, Pleiades MR, Altair ER, and Arcturus MS are reported in a graph, Anastasiou et al. 2013, 176, Fig. 2; those of Vega MR and ES for the latitude of Alexandria are on pp. A2-A3 in the appendices (in the online version). The Pleiades were assigned a location and a magnitude based on an aggregate of the ten brightest stars in the cluster (p. 185 note 16), whereas we have used Alcyone to stand for the cluster.

82 For the stars used in our calculations of the model parapegma, the average shifts from 400 BC to 100 BC were approximately 1.2 days later in the Julian calendar, and 3.6 days later relative to the solstices and equinoxes, with standard deviation approximately

stellar phenomena, one ought to be able to obtain a very rough estimate of when the observations were made, though an error of one day in the ancient determination of the solstices and equinoxes would throw the estimate off by about seventy years. The long term changes in the relative dates of the phenomena are probably too slow to be usable for dating parapegmatic observations or calculations.

Latitude, on the other hand, has a pronounced effect on the dates of stellar visibility phenomena. In general, for a Mediterranean range of latitudes, the date of a particular visibility phenomenon of a particular star will either tend to fall progressively earlier or progressively later with increasing latitude. The typical shift in date over the range 31°-41° is well over ten days, with no bias favoring a tendency to earlier or later dates with more northerly latitudes. Some events exhibit little or no shift of date; for example the setting dates (both morning and evening) of the Pleiades and Aldebaran shift by no more than two days over the ten degree latitudinal spread. At the other extreme, the settings of Arcturus and Alphekka, the risings of Capella, and all the phenomena of Vega all shift by fifteen or more (up to thirty-three for Capella's evening rising).

In principle, then, it should be possible to estimate the latitude for which a sufficiently large set of parapegma data was observed or computed. We can use as a test Ptolemy's *Phaseis,* which contains dates of phenomena of thirty bright stars that Ptolemy computed, according to the information he provides, from the coordinates and magnitudes in his star catalogue (*Almagest* 7-8) according to an *arcus visionis* model for a series of five latitudes corresponding to longest days ranging from 13.5 hours to 15.5 hours at half hour intervals.[83] As a subset of these data, we selected Ptolemy's dates for eleven stars,[84] for the latitudes having longest day 14 hours (30° 22′ according to Ptolemy, Almagest 2.6), 14.5 hours (36°), and 15 hours (40° 56′). The latitudes for which the PLSV model yields the best fit[85] are as follows:

1.2 days. These are slightly smaller shifts than the expected values (derived from the differences between the sidereal, Julian, and tropical years) because of uneven distribution of the stars in question.

83 Ptolemy appears to have used a model in which *arcus visionis* varied linearly as a function of azimuthal distance; see Graßhoff 1993.

84 Capella, Vega, Arcturus, Aldebaran, Sirius, Alphekka, Altair, Betelgeuse, Rigel, Bellatrix, and Alpheratz.

85 The date of a particular phenomenon corresponding to a given latitude was modelled as a least squares fit of a quadratic function to the dates calculated by PLSV for seven latitudes ranging from 28.5° to 43.5° at 2.5° intervals. We define "best fit" for the latitude as the latitude for which the standard deviation of differences between attested and PLSV dates is minimum, disregarding the mean difference, so that the result will not be affected

Longest day	Latitude (Ptolemy)[86]	Latitude (PLSV fit)	Mean difference[87]	Standard deviation	Number of dates
14 h	30° 22′	28° 58′	+3.4 d	3.0 d	43
14.5 h	36°	34° 36′	+3.3 d	3.2 d	41
15 h	40° 56′	39° 33′	+3.2 d	3.1 d	42

The PLSV model differentiates between the three sets of data remarkably well, with the estimated latitudes increasing from one set to the next by differences that are practically identical to the differences between the latitudes that Ptolemy ostensibly computed them from; but the estimated latitudes are consistently about a degree and a half too small. It is not clear whether this results from a bias in Ptolemy's method of calculation or in the PLSV model. In Fig. 3.14 the standard deviation is plotted for each data set as a function of the latitude for which PLSV dates are computed, showing that the quality of fit is quite sensitive.

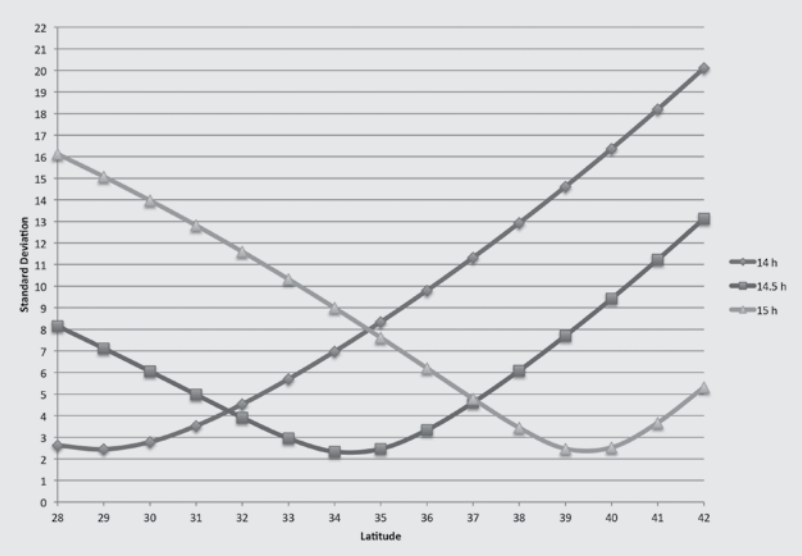

Fig. 3.14: *Fit of Ptolemy's data to modern theory calculations according to latitude*

by any systematic shift due to errors in the dates of the solstices and equinoxes assumed in the ancient sources.

86 From *Almagest* 2.6.

87 Dates relative to the summer solstice in 100 BC obtained from the PLSV model were subtracted from Ptolemy's dates relative to the date he assigns to the summer solstice (Epeiph 1 in the reformed Egyptian calendar).

Ptolemy's dates of phenomena relative to the summer solstice as he determined it average about 3.3 days later than the dates computed by the PLSV model for 100 BC relative to the summer solstice in that year. Assuming a precessional shift in dates of one day in seventy years, this would situate Ptolemy's calculations around AD 132, which on the face of it compares rather well with his epoch of AD 137 for his star catalogue (*Almagest* 7.4). The agreement is, however, to some extent coincidental, because Ptolemy's assumed solstices and equinoxes for his own time were about a day too late, so that his dates of the phenomena relative to his summer solstice average about a day less then relative to the true solstice. This might suggest that the PLSV dates are also about one day too early (we recall that they also averaged about 1.5 days earlier than dates computed by Anastasiou *et al.*).

We have also found latitudes that yield best fits for the zodiacal dates ascribed to Euktemon in the Geminos Parapegma (supplemented by other sources) and to Eudoxos in the Geminos Parapegma, as well as the Egyptian calendar dates in *PHibeh* 1.27 converted to zodiacal dates relative to the summer solstice date recorded in the papyrus.[88] For each collection of dates, we have estimated the latitude twice: (i) using all the attested phenomena according to the identifications of asterisms with specific stars in Appendix 1 except for a few extreme outliers, and (ii) limiting consideration to asterisms that can safely be equated, so far as visibility is concerned, with single bright stars: Sirius, Arcturus, Capella, Lyra (Vega), Aquila (Altair), and Hyades (Aldebaran). The results are as follows:

	Full set[89]				Single bright stars			
	Latitude	Mean difference	Standard Deviation	Number	Latitude	Mean difference	Standard Deviation	Number
Euktemon	33° 48′	–3.0 d	8.9 d	41	35° 13′	–3.1 d	7.2 d	24
Eudoxos	33° 41′	–1.0 d	9.1 d	47	35° 4′	+0.5 d	8.6 d	25
PHibeh 1.27	33° 59′	+3.0 d	9.0 d	22	35° 57′	+2.5 d	9.2 d	13

88 For *PHibeh* 1.27 we consider Pharmouthi 22, which is the third of the four consecutive days on which the longest day is stated to be in effect, to be the summer solstice, rather than Pharmouthi 24, which is the date on which the papyrus refers explicitly to the solstice but which is no longer assigned the maximum length of day. It is clear that the solstices and equinoxes of the papyrus were meant to be spread out as evenly as possible, with three 91 day intervals and one 92 day interval, while length of day is made to increase or decrease between extreme values of 10 and 14 hours by 1/45 hour per day, requiring five additional days of maximum or minimum length to be placed around the two solstices.

89 Omitting Euktemon's phenomena for Sagitta, Eudoxos's morning and evening settings of Corona, and *PHibeh* 1.27's phenomenon for Vindemiatrix.

Fig. 3.15 shows how the standard deviations vary when we compute the dates according to the PLSV model for a range of latitudes from 30° to 42°. It is clear that reducing the data set to the securely identifiable single bright stars makes the quality of the fit more sensitive in the lower range of latitudes, but all the sets show similar rapidly increasing trends in the higher latitudes, making it quite improbable that any of the three sources was based on observations or calculations for a latitude as far north as, say, 39°. If the fits to the single bright stars can be relied on and the PLSV model is not biased, all three sources would appear to reflect conditions around the latitude range 34°-37°. Correcting for the possible bias we found from the Ptolemy data, the range could shift northward to 35.5°-38.5°. From the little information we have concerning the localities where Euktemon and Eudoxos worked, this seems about right. Ptolemy asserts, we do not know on what authority, that Euktemon observed in Athens, the Cyclades, Macedonia, and Thrace, and Eudoxos in Asia (Minor), Sicily, and Italy, so that he considers their data to be valid for latitudes where the longest day is between 14.5 and 15 hours, i.e. between 36° and 40° 56′ (*Phaseis,* ed. Heiberg 66-67).[90] Hipparchos (ed. Manitius 28) concludes that Eudoxos's description of the system of constellations in his *Phaenomena* was written to fit the latitude of "Hellas," at 37°, and though the *Phaenomena* did not, to our knowledge, contain parapegmatic data, it is plausible that Eudoxos would have intended his dates of stellar phenomena to be applicable to the same approximate latitude. In any case Euktemon and Eudoxos are not likely to have compiled parapegma data at or for a latitude south of Rhodes, at 36°. As for *PHibeh* 1.27, it appears practically certain that the dates of phenomena in this papyrus originated in a source composed at a latitude much further north than Egypt.[91]

90 Ptolemy is speaking here of Euktemon's and Eudoxos's records of weather phenomena, but presumably the same would apply to their stellar phenomena.

91 Hibeh (el-Hiba) is in the Fayum, latitude 28° 46′, while the introduction of the text in the papyrus alleges that its teaching originated with a man from Sais in the Delta, Latitude 30° 58′.

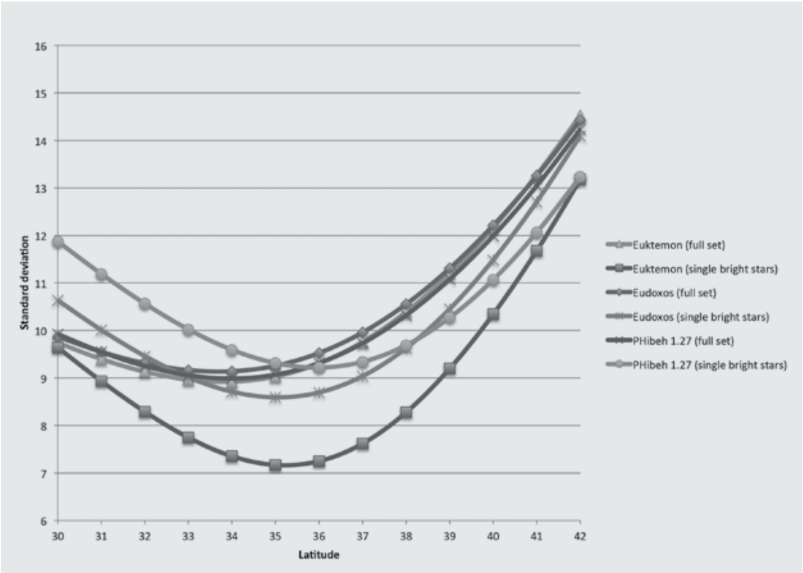

Figure 3.15: *Fit of parapegma data from the Geminos Parapegma and PHibeh 1.27 to modern theory calculations according to latitude*

The Euktemon dates average about 3 days earlier than those obtained from the PLSV model for 100 BC; if the PLSV dates are tending to be about a day too early as the comparison with the Anastasiou et al. model and Ptolemy's data suggest, the lead would increase to about four days. Euktemon's *floruit* is estimated as second half of the fifth century BC from the fact that Ptolemy (*Almagest* 3.1) associates him with Meton of Athens in the observation of the summer solstice of 432 BC, so the expected lead would be about 4.7 days if the Euktemon dates were relative to solstices or equinoxes that were accurate for his time.[92]

Since Eudoxos was active in the first half of the fourth century BC, it is at first glance surprising that the Eudoxos dates in the Geminos Parapegma have a very small average difference relative to the PLSV model, which is even positive if we consider only the bright individual stars. However, this seems to be at least in part a consequence of the way that the Eudoxos dates were incorporated into the Geminos Parapegma. While the Euktemon dates appear to have been incorporated on the assumption that Euktemon's solstices

92 Bowen & Goldstein 1988 argue that this was likely not a true observation of the date of the solstice; but for dating Euktemon's activity the question is immaterial. If the Egyptian calendar equivalent that was established in antiquity for the Athenian date of the Meton-Euktemon solstice was correct, which is unfortunately not certain, the true solstice was about a day later than the recorded date.

and equinoxes coincided with the first days of the relevant zodiacal months according to the Geminos Parapegma's own temporal framework (this is explicitly stated for the two equinoxes and the winter solstice), the Parapegma includes statements that Capricorn day 4 was the winter solstice according to Eudoxos and, 91 days later, that Aries day 6 was the vernal equinox. If, as seems likely, Eudoxos's solstices and equinoxes were supposed to be separated by near-equal intervals of 91 or (in one case) 92 days approximating equal quarters of the year, his summer solstice would have fallen on the Parapegma's Cancer day 2 or 3, and his autumnal equinox would have fallen on the Parapegma's day 1 or 2. This means that, depending on the season of the year, a Eudoxos date in the Parapegma can be as much as five days earlier relative to the immediately preceding solstice or equinox according to Eudoxos than relative to the Parapegma's own solstice or equinox. It is not clear what was the compilator's rationale for aligning the Eudoxos solstices and equinoxes with his own dates; perhaps he chose to equate the Eudoxos autumnal equinox with his own. An optimal alignment would likely have had the Eudoxos solstices and equinoxes falling two to four days earlier.

PHibeh 1.27 can be dated to before about 240 BC on grounds of archeological context and a dated document written on its back.[93] The positive mean differences, taken naively, would indicate a date around the late first century AD As was the case for the Eudoxos data, the solstices and equinoxes in the papyrus are at near-equal intervals of 91 and 92 days, this cannot by itself account for the large discrepancy since we are not now dealing with a case of data transferred from a zodiacal framework with equally spaced solstices and equinoxes to another framework with them unequally spaced. It seems, rather, that the stellar dates and the solstices and equinoxes have been incorporated in the papyrus's Egyptian calendar framework, likely from disparate sources, in an inconsistent way. The Egyptian calendar's steady shifting one day backwards every four years relative to astronomical phenomena may be the underlying cause, if the stellar dates were converted from some other chronological system to the Egyptian calendar according to appropriate equivalences for the time in question, and then combined with a set of Egyptian calendar dates for the solstices and equinoxes that had been approximately valid some decades earlier. The papyrus's equinoxes and solstices would have most nearly coincided with correct dates around 306 BC plus or minus a few years, so the conversion of the stellar phenomena would best fit a date around the end of the first quarter of the third century.

As the foregoing examples show, extracting estimates of the date and locality of origin of parapegma data from comparison with the PLSV model or other modern visibility models is not a simple matter. Calibration of the modern models is one problem: we have indications that the PLSV model may be resulting in systematic errors in estimated latitudes

93 Grenfell & Hunt 1906, 138-139.

(making them too far south) and dates (making them too late). But the chief difficulties arise from uncertainty in the alignment of the solstice and equinox dates assumed in the ancient sets of parapegmatic data with the astronomically correct dates and from the fact that probably none of our data sets represents a direct and "clean" record of original observations or calculations preserved in its original chronological framework. Evidence from the comparison with the modern model has to be considered in conjunction with whatever other information we have about the history of the data sets, and its testimony is clearest when negative; for example our analyses above render very doubtful the assumptions of *PHibeh* 1.27's editors that it was based on astronomical observations made in Egypt around 300 BC[94]

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94 J.G. Smyly in Grenfell & Hunt 1906, 140.

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