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Earth Deceleration from Ancient Solar Eclipses*

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Thirty-two ancient solar eclipse reports have been analyzed to determine the secular decrease in angular velocity of the earth. Seventeen are from *Chinese* reports in the literature. The computation, based upon Ephemeris Time and recently adopted astronomical constants, is described and the eclipse records discussed. Scatter in the computed mean acceleration indicates that some reports are erroneous or misinterpreted. The values group about -1.7×10^{-10} yr^{-1} (acceleration divided by velocity). Secular trends in the earth acceleration are noted, although ambiguous.

I. INTRODUCTION

THIS paper differs from the classical examination of ancient solar eclipses in two respects. First: Eclipses from Chinese antiquity have been researched and included to supplement those of the ancient Mediterranean civilizations. Second: The analysis is based upon modern adopted constants and upon Ephemeris Time. Previous classical discussions used Universal Time and the corrections for the change in earth spin were not properly included. Terms had been added to the lunar and solar longitudes but in retrospect we realize that other arguments (e.g., node, perigee) require corrections as well.

Many investigators have considered the secular terms in the longitudes of the moon, sun, and planets. The problem is not new, but only recently has the important contribution of the nonuniform rotation of the earth been properly appreciated. Spencer Jones (1939) determined the tidal "acceleration" (using the astronomical expression for the coefficient of the quadratic time term) of the moon on the ephemeris time scale to be -11.2 ± 0.5 sec century^{-2} from observations of the past $2\frac{1}{2}$ centuries. But irregular fluctuations obscure the slow secular increase in the length of day and one must take recourse in data from previous millenia in order to separate its secular increase from the effect of fluctuations. Although analyses of ancient solar totalities have been useful, they are very dependent upon the judgment of the investigator when interpreting old records.

The circumstance of a solar eclipse involves both the lunar and earthly decelerations and the separation of the two requires further assumptions. The constancy of either secular term is open to some debate. For example, deSitter (1927) reviewed the discussions of ancient eclipses by Fotheringham (1909, 1918, 1920a, b) and his conclusions imply a rotational earth acceleration of

$$\dot{\Omega}/\Omega=-(1.90\pm.06)\times10^{-10}\ \text{yr}^{-1}$$

and a lunar acceleration (in excess of the theoretical gravitational terms due to planetary perturbations) of -18.9 ± 1.8 sec century^{-2}. [The classical papers on this subject use the earth rotation as a time measure and results are usually quoted in universal time. Recognizing the variability of UT, this paper stresses the Ephemeris Time base. For those interested in converting these results (in ET) to UT basis: multiply the $\dot{\Omega}/\Omega$ (yr^{-1}) by -6.48×10^{9} to get the excess quadratic coefficient (sec century^{-2}) for the solar tabular mean longitude when times are in universal time; similarly the excess lunar secular term in UT is the lunar term in ET *plus* the solar secular term in UT times the ratio of lunar to solar mean motions (13.37), e.g., if in ET the $\dot{\Omega}/\Omega$ is -1.90×10^{-10} yr^{-1} and the excess lunar secular term is $-11.2''T^2$ (where T is in Julian centuries), then in UT the excess solar secular term is

$$-1.9\times10^{-10}(-6.48\times10^{9})T^2=1.23''T^2$$

and the lunar term becomes

$$-11.2''T^2+13.37(1.23'')T^2=5.2''T^2.]$$

Recall Spencer Jones' average value for the past 250 yr was -11.2 ± 0.5 sec century^{-2} for the moon. If this lunar variation is real and the accelerations of earth and moon were entirely due to tidal friction, then one might assume a constant ratio of secular accelerations of the moon and earth (on a gravitational time scale) and arrive at an estimate of the earthly rotational acceleration for the recent $2\frac{1}{2}$ centuries:

$$\frac{\dot{\Omega}/\Omega}{-11.2\pm0.5}=\frac{-(1.90\pm0.06)\times10^{-10}}{-18.9\pm1.8},$$

hence

$$\dot{\Omega}/\Omega\doteq-(1.13\pm0.20)\times10^{-10}\ \text{yr}.$$

Dicke (1965) selected data from Fotheringham of five Greek and Babylonian eclipses and obtained five average accelerations of the earth's rotation, when combined with Jones' modern lunar retardation. Dicke furthermore examined and estimated significant geophysical sources. One third of the observed earth slowing could not be readily accounted for and might

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imply a secular change of the gravitational constant $(1/G)(dG/dt) \doteqdot -4.\times 10^{-11}$ yr^{-1}.

Thus an improved determination of the secular earth rotation term is far from academic since it is a key to numerous geophysical, and perhaps cosmological, effects. The purpose of this study was to place the calculations on a modern footing, Ephemeris Time with presently adopted constants; and particularly to improve the statistics by including ancient Chinese eclipse observations.

II. ELEMENTS OF COMPUTATION

The calculation of an eclipse path is conveniently constructed in two stages: first the determination of positions of the sun and moon relative to the earth at the *ephemeris time* of interest; and second, the geometric construction of totality path from the astronomical data; local circumstances referred to the "ephemeris meridian." An estimate of the average terrestial rotational retardation may then be inferred from the discrepancy between the "ephemeris longitude" and the historical longitude of observation.

Ephemeride Sources

Newcomb's tables of the sun (1898) furnish the geometric mean longitude, right ascension, nutation, aberration, mean obliquity of the ecliptic, and parallax at the ephemeris time of conjunction, i.e.

$$L = 279\overset{\circ}{.}696678 + 1296\,02768\overset{''}{.}13T + 1\overset{''}{.}089T^2$$

where T is measured in Julian centuries from epoch 1900 Jan. 0.5 ET.

The *Improved Lunar Ephemeris* (1954) supplied the secular and harmonic terms necessary for calculating the lunar longitude, perigee, node, latitude, and parallax. These formulas for the coordinates are essentially those of Brown's tables of the moon except that the empirical term is removed and the mean longitude includes the adopted correction: $-8\overset{''}{.}72 - 26\overset{''}{.}75T - 11\overset{''}{.}22T^2$. Thus the lunar mean longitude contains a net quadratic term: $-4\overset{''}{.}08T^2$.

Computational Procedure

The calculation of near conjunction positions and of the eclipse curves was facilitated by coding a portion of the problem on an IBM 7094 digital computer (courtesy of the Princeton University Computer Center). The main steps in the analysis are briefly outlined as follows:

(1) The approximate time of conjunction for the eclipse of interest was obtained from Oppolzer's Canon (1962).

(2) The solar coordinates were obtained from Newcomb's tables and supplied as input data to the computer with the data and time.

(3) The computer first calculated the lunar position using the previously mentioned formulas. About one-quarter of the 1650 terms (each harmonic with quadratic arguments) were stored and used to attain positional accuracies of fractions of an arc second. "Additive terms" and "corrections for adopted constants" (*Improved Lunar Ephemeris 1952–1959*, pp. 290 and 347) were included.

(4) An iterative routine approached and determined the precise time and coordinates at conjunction (in longitude, not right ascension!).

(5) The computation of the totality path then proceeded by the Hansen method which is suitably abbreviated in Oppolzer's Canon. A map was printed indicating the totality belt expressed in ephemeris longitude (position on an imaginary earth which rotates *uniformly* at a rate defined by ephemeris time) and latitude.

(6) To facilitate estimating the effect of a slightly different secular term in mean lunar longitude from that suggested by Spencer Jones' investigation, another eclipse path was computed on the basis of an *increase* of the lunar secular term by 1.0 sec century^{-2}.

(7) The historical record defines the geographical area of observation and from the latitude boundaries one can determine the possible ephemeris longitudes on the calculated totality path.

The equivalent average acceleration of the earth $\dot{\Omega}$ is obtained from the difference between the observed longitude $\lambda_0 \pm \delta\lambda_0$ and the calculated ephemeris longitude $\lambda_c \pm \delta\lambda_c$ accordingly. If d is the displacement of the ephemeris meridian from Greenwich at the epoch base time, then $\lambda_0 - d - \lambda_c \pm (\delta\lambda_0 + \delta\lambda_c) = -\frac{1}{2}\dot{\Omega}T^2$, the relative angular velocity change would be

$$\frac{\dot{\Omega}}{\Omega} = \frac{\lambda_0 - d - \lambda_c}{-6.555\times 10^6 T^2}\ \text{century}^{-1},$$

where λ is degrees eastward, and T is Julian centuries from 1900 Jan 0.5 ET.

(8) Sundry Details. To be consistent with adopted values in the American Ephemeris (1961), the following constants were taken: 0.2724807 as the ratio of the moon's radius to the equatorial earth radius, $15'59\overset{''}{.}63$ for the mean semidiameter of the sun, $8\overset{''}{.}80$ as the mean solar parallax. Although recent determinations establish the flattening of the earth's figure to be 1/298.3, again the adopted ephemeris value of 1/297 was retained.

The elements ΔB and ΔL (hourly variations of shadow circle center; in Hansen's theory and defined in Oppolzer's introduction) were evaluated only once, at conjunction, and these values used throughout the path.

Accuracy

The precision of the calculated earth slowing is restricted by the width of the totality belt and hence the path need be known only to a fraction of its breadth (widths average one or two degrees).

"Double Precision" arithmetic (16 significant digits) was employed when necessary to calculate conjunction positions, which were determined with an accuracy of better than an arc second.

The program was primarily tested by comparing the tabular coordinates of the moon in the Improved Lunar Ephemeris with coordinates calculated by the computer code for 24 April 1948. The longitude agreed to $0''.7$, the latitude to $0''.3$, and the parallax to $0''.6$; all within the expected deviation.

The path computation was checked using the typical solar eclipses of 20 July 1963 and 30 May 1965 as test cases. The central lines and widths agreed within 20% of the width.

III. ECLIPSE REPORTS

Untrained in sinology and ignorant of Asian tongues, the author has had to rely upon secondary references. This section summarizes the readily available facts concerning early Chinese and European eclipses. Incidentally, a brief but illuminating review of Chinese astronomy is presented by Needham (1959).

Prior to the seventh century B.C. there are no certain totality descriptions in the Chinese literature. From the seventh to second centuries B.C. there are several records which may be helpful. The Former Han Dynasty (206 B.C. to A.D. 23) kept systematic records which have been translated and much commented upon by Dubs (Pan Ku 1955).

(1) Shu-King eclipse, around 2000 B.C.: The earliest reference appears in the Shu Ching (Book of Historical Documents) and by tracing emperors can be dated within two hundred years of 2000 B.C. The magnitude remains in considerable doubt since the legend relates: "sun and moon did not meet harmoniously . . .." Various dates have been proposed in the literature and two have been checked (negative astronomical dates differ by one year from historical calenders e.g., −1904 is 1905 B.C.) −1904 May 12, −2136 October 22. An exhaustive search of all conjunctions for this period was not completed because there yet exists no criterion for selection. Its extreme antiquity continues to intrigue in spite of the dubious qualities of place, totality, and date.

(2) Oracle Bone inscriptions of the latter part of the Shang Dynasty (1398–1112 B.C.) mention several lunar and one solar eclipse. For lack of detail it has not been investigated.

(3) Lu: The Chun Tsiu (History of Lu) recorded 36 eclipses which fortunately coincide with Ptolemy's Almagest listing and permit a definite correspondence with the Chinese calendar. The translation by Legge (1872) indicates totality for those of −708 July, −600 September 20, and −548 June 19. The first two record "the sun was totally eclipsed," the third says "sun was completely eclipsed." These have been analyzed assuming (Herrmann 1935) the State of Lu extended from 116 to 119 deg east longitude λ, and $34\frac{1}{2}$ to $36\frac{1}{4}$ north latitude ϕ. The capital had coordinates $\lambda 117^\circ.$, $\phi 35^\circ.6$.

(4) other Lu: A comparison of Hoang's Catalogue (1925) with Oppolzer's Canon indicated four eclipses (−663 August 28, −654 August 19, −573 October 22, −510 November 14) which *might* have occurred at or near the capital. Since the observed magnitudes are unknown, any results for these are speculative.

(5) Needham says that the Shih Chi recorded stars could be seen during the eclipses of −299 July 26, −381 July 3, and −441 March 11. The capital was at $\lambda 180°58'$, $\phi 34°17'$ and the Chinese states extended over $\lambda 109^\circ.(+9, -4)$, $\phi 34^\circ. \pm 4$. But Oppolzer's map shows the latest eclipse above 45°. latitude so doubt is cast upon the location of the other two; that is, these may have been reported from afar.

(6) Han Eclipses: Documents of the Han Dynasty from −205 to 23 A.D. have been carefully scrutinized by Dubs (1938) and he finds 55 solar eclipses were recorded. Of these, only five were described as total: −187, −180, −79, −27, and +2. The important sources were the Annals of the Shih-chi and the Han-shu (History of the Former Han Dynasty), and Chap. 27 in the Han-shu entitled "Treatise on the Five Elements." After comparing coincident reports, Dubs concludes that the "Treatise" list was compiled by astronomers at the capital, Ch'ang-an ($\lambda 108°58'$, $\phi 34°17'$) whereas the Annals include reports from possibly all of China. Since detailed accounts seem to end in Chap. 27 after 28 B.C., he presumes that later reports may originate outside. Such assumptions infer that only one total solar eclipse was observed at the capital in this period since the five were described as follows:

−187 July	17	Treatise says "almost total"; Han-shu Annal records "and it was total."
−180 March	4	Total by both Annals.
− 79 Sept.	20	Treatise says almost total; Annals say total.
− 27 June	19	Treatise says "not completely total, but like a hook"; Annals say total.
+ 2 Nov.	23	Chapter 27 describes it as total.

The −180 eclipse may be taken as total. Nevertheless four of these were analyzed (the −79 was discarded since Oppolzer's map indicates totality very far from the capital) and bounds could be set by those assumed to be outside.

(7) +1221 May 23: A totality was observed at the Kerulen River in Mongolia. Waley (1931) translates: ". . . there was a total eclipse of the sun, . . . stars were visible." He notes "total eclipse" is translated from an archaic phrase! From the narrative, the event happened 8 days after reaching Lake Kerulen and 3

TABLE I. Acceleration computed for European and Chinese eclipses.

Eclipse	Date[a]	Conjunction ET (h)	Conjunction Long.[b]	Place assumed[g]	$\dot{\Omega}/\Omega \times 10^{10}$ yr^{-1} [e]
Babylon	−1062 July 31	11.766	116°.577	Babylon	−1.62±.03
				Nippur	−1.65±.03
				Euphrates Mouth	−1.76±.05
Eponym-Canon	− 762 June 15	13.357	74.772	Ninevah	−1.85±.08
				Assyria	−1.87±.25
Archilochus	− 647 April 6	13.115	9.085	Paros	−1.62±.08
				Thasos	−1.79±.08
Thales	− 584 May 28	18.904	59.721	Asia Minor	−1.82±.23
				SW river Halys	−1.79±.14
				Sardis	−1.61±.08
				Gulf of Issus	−1.65±.09
Pindar	− 462 April 30	15.923	33.411	Thebes	−2.02±.12
Thucydides	− 430 Aug. 3	18.638	124.637	Crescent at Athens	<−1.45
Agathocles	− 309 Aug. 15	11.492	136.708	off S.W. Sicily	−1.71±.14
Hipparchus	− 128 Nov. 20	15.928	236.185	Hellespont	−1.61±.02
Caesar	− 50 Mar. 7	14.263	344.275	annular at Rubicon	−1.77±.12
Phlegon	+ 29 Nov. 24	11.754	240.964	Nicaea	−1.56±.04
Plutarch	+ 71 Mar. 20	11.753	357.573	Delphi or Chaeroneia	−1.54±.02
Bavaria	840 May 5	7.895	45.675	Bavaria	>−1.36
Stiklasted	1030 Aug. 31	14.517	163.047	Stiklasted	−1.77±.04
Flanders	1133 Aug. 2	12.247	135.861	Flanders	>−0.13
				Scotland	−2.6 ±2.1
Bate	1310 Jan. 31	12.763	319.516	Maline	−1.08±1.70
				Liege	−2.16±1.7
Shu-Ching	−1904 May 12	13.424	32.953	$113\frac{1}{2}\pm2\frac{1}{2}$, $\phi34.4\pm1.1$	−1.50±.06
	−2136 Oct. 22	13.794	191.089	$113\frac{1}{2}\pm2\frac{1}{2}$, $\phi34.4\pm1.1$	−2.01±.08
Lu-Hoan	− 708 July 17	11.702	106.247	Capital	−1.70±.04
				State of Lu	−1.70±.10
Lu-Siuen	− 600 Sept. 20	11.743	170.820	Capital	−1.94±.04
				State of Lu	−1.95±.10
Lu-Siang	− 548 June 19	9.439	80.411	State of Lu	−1.60±.26
Lu-Tchoang	− 663 Aug. 28	11.735	147.259	State of Lu	−1.31±.12
Lu-Hi	− 654 Aug. 19	11.094	138.214	State of Lu	−1.51±.11
Lu-Tcheng	− 573 Oct. 22	5.869	202.245	c	...
Lu-Tchao	− 510 Nov. 14	7.205	226.415	c	...
Yng	− 441 Mar. 11	...	...	d	...
Yng-Hien	− 381 July 3	4.838	94.366	Domain	−2.16±.40
Yng-Tchao	− 299 July 26	4.136	117.566	Domain	−1.93±.62
Han-Hoei	− 187 July 17	9.980	110.002	Capital	−1.82> e> −1.79
Han-Kao	− 180 Mar. 4	9.363	340.633	Capital	−1.58±.07
Han-Tchao	− 79 Sept. 20	...	...	f	...
Han-Cheng	− 27 June 19	5.601	84.301	hook at Capital	−1.17 <e<−1.39
Han-Ping	+ 2 Nov. 23	4.613	239.070	Capital	−1.27±.01
Kerulen	1221 May 23	4.641	68.406	112°, $\phi47\frac{1}{2}$°	−1.00 <e<2.8

[a] Greenwich civil date, reckoned from midnight.
[b] Apparent celestial longitude in degrees.
[c] Discarded because path occurred 10's of degrees north of Lu.
[d] Discarded, path above 45° latitude.
[e] $\dot{\Omega}/\Omega \times 10^{10}$ yr^{-1} (acceleration divided by velocity).
[f] Discarded, path far from capital.
[g] See Sec. III of text.

days before they left the southern part of the river. I estimate their position was near $\lambda112°$, $\phi47\frac{1}{2}°$.

European Records

Fotheringham (1920) discussed 11 eclipses spanning 13 centuries. Nine for which an assumption of totality and place can be made are summarized as follows:

(1) Babylon −1062 July 31; Reasonable doubt remains concerning details of this ancient event. The account reads "... on the 26th day ... day was turned to night, and fire in the midst of heaven ...." Fotheringham assumes 26 is a typographical error for 28, the day on which totality occurred. Although generally ascribed to Babylon ($\lambda44°.5$, $\phi32°.5$), the city of Nippur (45°.2, 32°.2) and the Euphrates mouth ($47\frac{1}{2}°$, 31°) will also be considered.

(2) Eponym Canon −762 June 15; After mentioning the cities of Gozan and Assur, the Chronicle says "... the sun was eclipsed." Hence the place is in serious doubt although Ninevah, where the document was found [$\lambda43.3$, $\phi36.4°$ (Shepherd 1911)], is used here. Much wider limits cannot be ruled out so Fotheringham's Assyrian region was also checked.

(3) Archilochus −647 April 6; The islands of Paros ($\lambda25\frac{1}{2}°$, $\phi37°$) and Thasos (24.6°, 40.8°) are equally possible so the two cases are considered separately.

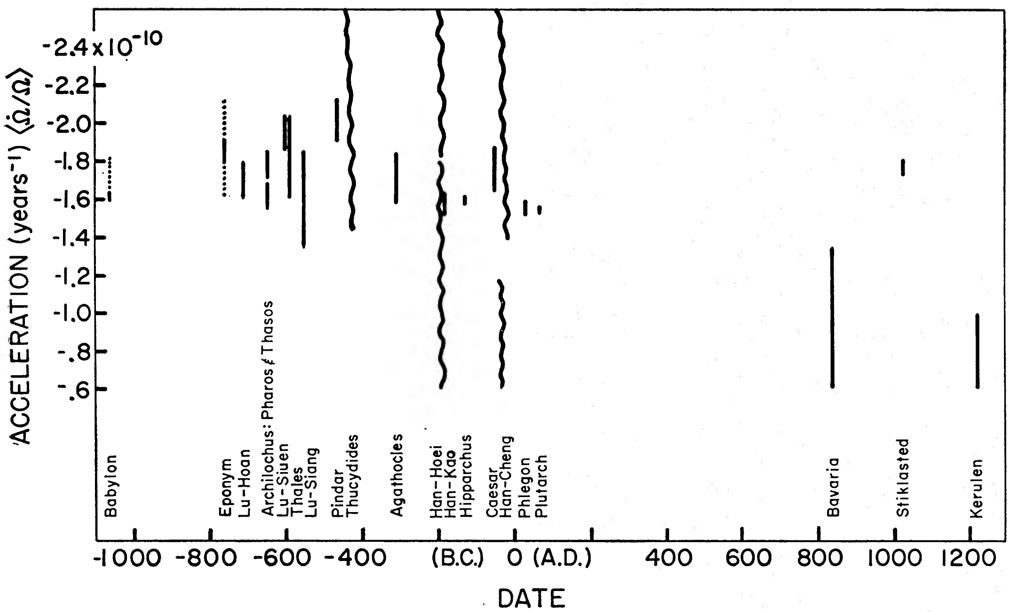

FIG. 1. Rotational acceleration of earth (from selected eclipses) $\dot{\Omega}\,\Omega$). | Primary choice, ⁝ Alternative region, ≀ Inference from partiality.

(4) Thales −584 May 28; The eclipse took place during an engagement between the Lydians and Medes somewhere in Asia Minor (λ27° to 36°, ϕ37° to 41°). Three specific places were also tested: southwest corner of river Halys (34°±1, 38¾±¼); Sardis (28°.1, 38½°); Gulf of Issus (35¾°, 36½°).

(5) Pindar −462 April 30; the presumption that a totality darkened Thebes (23°.3, 38°.3) is tested.

(6) Agathocles −309 August 15; totality is unquestioned but the place is uncertain since it was observed aboard ship one day out of Syracuse headed for Carthage. I have assumed a position of 13° E longitude and 37° N latitude. The very wide totality belt of about six degrees limits useful conclusions.

(7) Hipparchus −128 November 20; Accepted Fotheringham's zone in the Hellespont (26°.6, 40°.4 to 26°.3, 40°.0).

(8) Phlegon +29 November 24; Nicaea (29°.6, 40°.4) is assumed although any part of Bithynia might be permitted by the ambiguous text.

(9) Plutarch +71 March 20; Delphi (22°.52, 38°.50) or Chaeronia (22°.83, 38°.48).

(10) Thucydides −430 August 3; the crescent description sets a lower bound on the secular deceleration, assuming partial at Athens.

(11) Caesar −50 March 7; this annular eclipse is assumed for the Rubicon river near λ12⅜°, ϕ44°.1

An examination of more recent eclipse sightings should reveal something about the variation in earth-moon accelerations.Unfortunately the errors are larger due to the relative importance of path width to longitudinal retardation (the latter being quadratic in time). Still, some striking medieval cases were investigated.

Bavaria +840 May 5; Johnson (1874) claims that total darkness enveloped Bavaria up to five minutes in places. I considered the region bounded by 12°±1° longitude and 48½°±1½° latitude.

Stiklasted +1030 August 31; Dreyer (1877) mentions the sun becoming totally eclipsed and a red light appearing around it during the battle at Stiklasted (11°.6, 63°.8) in Norway.

Flanders +1133 August 2; Johnson assures us it was seen in Flanders according to Calvisius and the stars appeared. The area λ2½°±1°., ϕ50½°±½° was tested.

Bate +1310 January 31; Henry Bate of Maline observed (Sarton, 1931) an annular eclipse. Maline (λ4°.5, ϕ51°.1) and Liege (λ5°.7, ϕ50°.6) were alternately assumed.

IV. RESULTS

The results of the analysis appear in Table I and are illustrated in Fig. 1. The scatter in the computed mean secular acceleration indicates, as expected, that some inferences of totality are likely wrong, assuming that random variations in the earth rotation are unimportant in an average over this time interval. Certain, somewhat subjective, choices are made as follows:

The records favor acceptance of Hipparchus (−128) and Archilochus (−647) eclipses without reasonable question although −647 offers two possibilities. The Han eclipses of −187 and −27 furnish forbidden values of $\dot{\Omega}/\Omega$ since they are partial within the capital although total nearby. Presumably Dubs is correct in his criticism of the Han-Ping (+2) case since its acceleration prediction is unreasonably small. Phelgon (+29), Plutarch (+71), and Han-Kao (−180) may be tentatively accepted since they closely agree.

Two trends are inferred by the Archilochus dichotomy. Either the secular deceleration sharply increases into the past (favoring island Thasos) or changes slightly (Paros choice). The former situation is supported by the three Lu eclipses (−708, −600, −548), however the Lu-Siuen report is crucial. The latter trend reconciles the ambiguous Babylonian (−1062) account but would reject the −600 Chinese report (the solid line in Fig. 1 assumes Babylon totality, whereas the upper dotted continuation assumes totality further southeast along the Euphrates river).

The remaining cases are either too indefinite in their predictions or strikingly inconsistent with the previous determinations. The Ninevah hypothesis for the eponym canon eclipse results in a large deceleration although allowance for central Assyria considerably widens the choice. Pindar appears unlikely at Thebes. The reasonable consistency of the Agathocles (−309) value supports the hypothesis of a southern route around Sicily. The limits set by the Bavarian (+840) and Kerulen (+1221) samples contradict the Stiklasted (1030) result so more accurate reports for the early medieval period are being sought to fill in this gap.

Unfortunately the scatter and uncertainty prevent an unambiguous determination of any secular variation in the acceleration terms. The grouping in Fig. 1 weakly suggests however an increase in deceleration in the past, which Dicke (1965) points out could be due sea level rise with no isostatic adjustment.

Should the lunar secular term be changed, a corresponding correction must be applied to the acceleration of the earth's rotation. This coefficient is, on the average, about 0.12×10^{-10} yr^{-1}/sec century^{-2}. For example, if the lunar term be increased by $0''.5$ century^{-2} over the value expressed by Spencer Jones, then the values of $\dot{\Omega}/\Omega$ in Table I would be increased approximately 0.06×10^{-10} yr^{-1}.

Further information or suggestions, particularly concerning additional early eclipse reports, would certainly be appreciated by the author.

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