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Lunar Eclipse Astronomy

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Lunar Eclipse Astronomy

by Kristian Peder Moesgaard *

0: Ouverture

In continuation of (KPM:2010) =

Kristian Peder Moesgaard (2010). *Mean Motions in the* Almagest *out of Eclipses.* RePoSS: Research Publications on Science Studies 8. Århus: Department of Science Studies, University of Aarhus. URL://www.ivs.au.dk/reposs.

we turn to producing high precision astronomy from nothing but keeping track of lunar eclipses. In Antiquity such astronomy flourished notably by way of column E in Babylonian system A lunar ephemerides. Possibly this laid the foundations of the *Almagest* theories and left its mark on the Antikythera mechanism.

The luminaries passing by the nodes of the lunar orbit is controlled by the relation **5458 M s = 465 Yd = 5923 Md.** With 2 eclipse warnings per draconitic year the monthly motion of the sun becomes 465/2729*180° = 30°40'14"04'''. This makes up a common high precision foundation stone for Babylonian and early Hellenistic astronomy.

30°40'14"04'''

A trifling deviation from modern standards hides in the monthly 4''' above, or 1,6' per century. It is inconceivable that this accurate parameter came up by chance. It must needs be rooted in extensive series of lunar eclipse observations over a prolonged period. And once found in Babylon it had to be adopted by Greek astronomers by virtue of its predictive power. Ptolemy, in his *Almagest,* corrected the rate by about 4''', but ironically to the wrong side.

> *Babylonian* solar motion, 225/2783*360°/Ms = 29;06,19,01°/Ms falls behind modern ***anomalistic*** motion by 0,25"/Ms, and the *Almagest* value (120*360° + 23°)/1485 – 1°/1237 = 29;06,20,07°/Ms, behind modern ***sidereal*** motion by 0,08"/Ms

For the other period relation behind column E, **2783 M s = 225 Y(?)**, the situation is a bit more complicated. In antiquity the years involved were probably held to be *sidereal.* After all the eclipses were seen against a background of fixed stars. But the observations aimed at pinning down the unequal spread of eclipses all around in the zodiac, and this inequality is governed by the *anomalistic* year. So no wonder that the Babylonian "sidereal" year came out close to the actual anomalistic measure, whereas Greek astronomers had a better grip on the sidereal drift of eclipse locations. But in return they totally missed the mark as regards the anomalistic year.

Anyway this paper aims at testing column E against lunar eclipse data from Antiquity selected to illustrate both its long term stability and its capacity to imitate the inequality depending zodiacal locations. But here let us expose the predictive power of column E at more recent times. Tycho Brahe, in his *De Stella Nova,* deals with a lunar eclipse of magnitude 18,7 in december 1573. The Full Moon goes with number GN 31835, and col. E predicts an eclipse of magnitude 11,4, i.e. a deviation of -7,3 units accumulated during almost two millennia. Again in June 1974, in Torrild vicarage garden, I watched together with my 5 weeks old daughter Marianne the full moon bereft of its light except for a strip of say one sixth part at its lower limb, i.e. eclipse magnitude about 10. For the full moon no. GN 36788 col. E yields magnitude 21,1, or a deviation of -11,1 units accumulated during almost 2,5 millennia.

1: *Ancient Ephemeris Time:* when do lunar eclipses occur ?

Lunar eclipses occur only at full moon. So in lunar eclipse astronomy the natural time measure counts *synodic months, Ms,* between full moons, identified e.g. by their - integral - Goldstine Numbers, *GN,* (Goldstine: 1973). Ephemerides from Babylon nicely reflect this, dealing line by line with consecutive full moons - or new moons given by half-integral GN-numbers and occasionally producing solar eclipses.

Measured in days the month changes considerably around 29,5. So day and month cannot both be constant. The case, however, for constant months and days of variable duration is no more strange than daylight lasting twelve "seasonal hours" of variable duration. Anyway, the ancient month was subdivided into *tithis = 1/30*Ms,* in the short run close to days. In general fractions of the months may be measured by *lunar elongation*, e.g. half moons on the wane with elongation 270° go with the timing GN + 0.25. At Nabonassars epoch GN was 3142,69616, new moon 3142,5 plus the radix of elongation, 70;37°/360.

Ancient Ephemeris Time does away with any concern about the equation of time which springs from the annual variation of the *daily* rotation of the *earth* measured along the *equator* (KPM:1983a&b).

2: *Full Moon Serpent:* where do lunar eclipses take place ?

Lunar eclipses occur near the ecliptic right in the middle of the zodiacal belt, and closer than 11,5° to the nodes of the lunar orbit. So by hindsight we may expect lunar eclipses at the fraction *f* of any number of succesive full moons:

$$f \approx 4*11{,}5/360 \qquad (1)$$

The lunar nodes, however, are invisible, and in addition moving at their own rate. But 235 months come close to 19 and 254 revolutions of the sun and the moon, respectively, say among the stars, and in the bargain close to 20 and 255 revolutions in relation to the lunar nodes:

$$\begin{aligned}235 \text{ Ms} &= 19 \text{ "synodic" years} \approx 20 \text{ draconitic years}\\ &= 254 \text{ months} \approx 255 \text{ draconitic months} \qquad (2)\end{aligned}$$

This resonance creates a quasistationary *Full Moon Serpent* out of 235 consecutive full moons pictured simultaneously on a star map. The pattern includes 35 sinusoidal waves that span the zodiac twice and by their mutual intersections (knots) produce 35 discrete positions pregnant with lunar eclipse warnings. Now f*235 = 30 whence some of the knots must do without an eclipse event.

Figure 1 presents the full moon serpent from GN 6580 (-468 JA) through GN 6814 (-450DE), (KPM:1980, p. 52; KPM:1983a, p. 6; and KPM:1983b, p. 48). The full moons are numbered: n = 1, 2, ... 235 from the beginning of Aries and they proceed by 19 "steps" pr. month. The synodic(!) longitude numbers in the Figure result from:

$$n = (GN + 4)*19 \text{ modulo } 235 \qquad \& \quad GN = 99*n - 4 + p*235 \qquad (3)$$

The 35 potential eclipsing "knots" are also numbered in the Figure: N = 0, 1, ... 34. After three eclipses at a particular knot for GN = x, x+235 and x+470 you might expect a fourth eclipse for GN = x+705. But this never happens. The fourth eclipse occurs for GN = x+804, initiating another eclipse triad at the neighbouring step, 804*19 = 65*235 + 1. This drift of eclipsing knots by one step pr. 804 months continues for more than one and a half millennium. The sun passes about 19/235*35 knot intervals pr. month, or more precisely 2275 intervals pr. 804 months. A central eclipse occurred at knot 20 for GN = 9997 (KPM:1980, p. 69) whence other knot numbers pointing to possible eclipse longitudes result from:

$$N = 20 + (GN - 9997)*2275/804 \quad \text{modulo } 35 \tag{4}$$

No.	Time GN//YearMM	Place n//N	Magni- -tude	Rem.
1	3465//-720MR	111 // 17	Total	Syst. A'
2	3477//-719MR	104 // 16	3 S +	Syst. A'
3	3483//-719SE	218 // 33	>6 N +	Syst. A'
4	4703//-620AP	133 // 20	3 S -	1°/cent.
5	5918//-522JL	188 // 28	6 N -	
6	6182//-501NO	34 // 5	3 S -	Hipp.
7	6311//-490AP	135 // 20	2 S -	1°/cent.
9	7655//-382DE	56 // 8	Small(-)	
10	7661//-381JN	170 // 25	3 hrs. (-)	
11	7667//-381DE	49 // 7	Total	Hipp.
30	9903//-200SE	233 // 34	3 hrs. (-)	
31	9909//-199MR	112 // 16	Total	
32	9915//-199SE	226 // 33	Total	
33	10232//-173AP	139 // 20	7 N +	1°/cent.
39	10578//-145AP	133 //19	Total	
42	10637//-140JA	79 // 11	3 S +	
43	10713//-134MR	113 // 16	Total	
54	13917//125AP	124 // 17	2 S -	
63	14017//133MY	144 // 20	Total	1°/cent.
69	14035//134OC	16 // 1	10 N +	
73	14052//136MR	104 //14	6 N -	

The scheme above surveys 21 lunar eclipse reports from the *Almagest*. The leftmost numbers refer to Olaf Pedersens catalogue of *Almagest* observations (O. Pedersen: 1974, pp. 408-422). Elsewhere we have told how Hellenistic astronomers built upon the "synodic" year = 235/19 Ms. Using the eclipses nos. 6 and 11 they finetuned not only a complete model of solar anomalistic(!) motion, but also the key intervals between solstices and equinoxes presented nevertheless later as the empirical(!) basis behind their model and tables for the tropical(!) solar motion. The trifling difference between a genuine "synodic" solar motion,19/235 rev./Ms, and the finetuned *Almagest* value, (120 + 23/360)/1485 rev./Ms, amounts to a solar drift of 1,1'/century. We found also the 1°/century precession reliable when related to the rate of drift between the fixed stars and the eclipsing knots as revealed by the eclipses nos. 4, 7, 33 and 63 at knot no. 20. So in spite of their sloppy suggestions for the tropical and anomalistic years the Greeks succeeded in building a sound sidereal doctrine of astronomy (KPM:2010, pp. 10-20).

3: Annual anomaly in Babylonian column E

To be sure the Full Moon Serpent does not represent the path of motion for the full moon. Actually full moon "events" exist only momentarily when the sun and the moon are seen in opposite directions. But whenever this happens the event is located somewhere on the Full Moon Serpent. Time and again the events are directly observable in the shape of eclipses, and and then always close to one of the 35 knots of intersection.

Now neither the 235 steps of longitude nor the 35 eclipse warning knots are distributed evenly in the Zodiac. From Figure 1 it is evident that the *knots nos. 15 and 33 are directly opposite to each other*. So from Virgo to Pisces you meet 18 knot intervals each of 10° on the average, but from Pisces to Virgo only 17 intervals of about 10;35°. This is seen in Figure 2 which also counts 114 steps of 180°/114 = 30°/19 = 1;35° and 121 steps of 28;20°/19 = 1;21° in the two halves of the Zodiac respectively. Thus we produced the two solar velocities in Babylonian System A' tables. The round value of 30°/Ms became canonical and survived also in the System A theory. The System A' year of 12;23Ms equals 743/60, i.e. 743 basic steps and a monthly solar progress of 60 steps, and it determines the lengths of the fast and the slow arc respectively to 164;30°, or 329 steps of 0;30°, and 195;30°, or 414 steps of 0;28,20°. The said year is more than 10 hours above its mark, but this does no harm to the following short term use of the theory.

Thus far any close combination of eclipses in Virgo and Pisces would lead to similar parameters. However, the eighth century B.C. triad of eclipses, nos. 1-3 links with the jumping longitudes between the fast and slow arcs of the System A' theory - and of the canonical System A theory as well (cf. KPM: 1980, p. 87-90). This is surveyed in Figure 3. With the eclipses nos. 1 and 2 located symmetrically before and after the longitude, 179°, of jumping from slow to fast arc, and at the same time close to Spica Virginis we find eclipse no. 3 close to the other jumping point of System A' at the longitude 343,5° - and in the bargain almost opposite to the System A jumping longitude 163°.

The average "step" in system A' is 360°/743, whence the fast arc surpasses the average by 329*(0,5° - 360°/743) = 5,1°. Half of this, 2,55°, represents a rather sound value for the maximum annual equation in the distribution of full moons. Similarly the System A year of 12;22,08 Ms equal to 2783/225 goes with 2783 basic steps and a monthly solar motion of 225 steps. This splits into 1455 steps of 0;08° and 1328 steps of 0;07,30°. So for the double maximum equation we get 1455*(0;08° - 360°/2783) = 5,8°, and the equation itself amounts to 2,9°, which does not make for an improvement on the system A' equation.

Now the system A year of 12;22,08 Ms is a rather sound period for the motion of the sun in its own orbit. It hits the true anomalistic year to within 1,3 minute, or a solar drift of

-5,3' per century (KPM:2010, p. 13). It is commonplace, however, to think of this year as sidereal, and possibly ancient astronomers would agree as indicated by the reference to Spica above. If so, you need not speculate, neither how the Babylonians reached the impressive level of precision, nor why the Greeks did not copy this parameter, but introduced their own sidereal year of 12;22,07,30 Ms equal to 1979/160. The Babylonian choice may stem from rounding to two sexagesimal places, and the Greeks could be sure that lowering the value by almost 6 minutes represents an improvement.

At all events the Babylonian tables contain only actual solar positions at full moon in their unequal distribution among the stars of the zodiac, but no mention at all of solar orbit, apsidal axis of symmetry, mean motion, or "equations to be added or subtracted" (*prosthaphairesis* (O. Pedersen:1974, p.140)). Such notions entered the scene by way of Greek geometrical framework. Still it is fascinating that reliable anomalistic(!) information hides in Babylonian col. B of solar longitude based on the sidereal(!) relation: 2783 Ms = 3008 M* = 225 Y*. Numbering the longitudinal steps from n(B) = 0 at the jumping point from slow to fast arc, 163°, via n(B) = 1455 at the other jumping point, 357°, to n(B) = 2783 after a full revolution, you get any step number by:

n(B) = 225*GN - 1644	modulo 2783	(5)

and the solar longitude/anomaly itself by:

B = 163° + n(B)*0;08°	for 0 ≤ n(B) ≤ 1455	
B = 357° + (n(B) - 1455)*0;07,30°	for 1456 ≤ n(B) ≤ 2782	(6)

Finally the full moon, or anti-solar, longitude result from adding/subtracting 180°.

In the scheme next page the *Almagest* eclipses are connected with their corresponding solar longitudes as drawn from equations (5) and (6), and also with the solar anomalies equal to col. B minus 70°. The 70° longitude for the "apogee" is chosen a quadrant (90°) plus the maximum equation (almost 3°) before the jumping longitude 163°. See Figure 3.

The Scheme also brings solar anomalies as calculated by Hellenistic and modern standards. The Greek entries result from the mean anomalies 168,5° at no. 6 and 120 revs. + 191,5° at no. 11, (Cf. KPM:2010, p. 16). The modern mean anomalies are found from my reference tables (KPM:1975) averaging over the period from -500 to -100. Both sets of mean values are turned into true anomalies by equations up to the *Almagest* maximum of 2;23°.

The pale blue columns of deviations represented also graphically in Fig. 4, (cf. KPM: 2010, Figure at p. 16) suggest the following route of development. The Babylonian System A solar longitudes of column B probably originate in the *unequal distribution* of lunar eclipses *among the stars* in the Zodiac. So you may think of the year involved, 2783/225 = 12;22,08 Ms, both as *sidereal* and *anomalistic*. Concerning the sidereal rotation the Greeks knew better from the drift of the eclipsing knots among the stars. Nevertheless they possibly adopted the correct(!) Babylonian anomaly (i.e. the apogee) about 200 BC.

But Alas! They took the tropical and anomalistic years to be equal and moreover identical to the "synodic" year underlaying the full moon serpent, and so possibly governing the entire business of anomaly. To conclude: in Hellenistic astronomy the solar anomaly from the very beginning went astray by well over a full degree per century.

Eclipses in *Almagest*			Hellenistic		Babylonian, Syst. A			Modern
No	Time GN//YearMM	Place n//N	True Anomaly	Hell. - Mod.	Solar Col. B	Col. B -70	Bab. - Mod.	True Anomaly
1	3465//-720MR	111 // 17	288;42	-388'	5;37,30	295;37,30	27,5'	295;10
2	3477//-719MR	104 // 16	278;04	-390'	355;08	285;08	34'	284;34
3	3483//-719SE	218 // 33	87;57	-393'	164;04	94;04	-26'	94;30
4	4703//-620AP	133 // 20	321;40	-304'	36;52,30	326;52,30	8,5'	326;44
5	5918//-522JL	188 // 28	42;35	-242'	117	47	23'	46;37
6	6182//-501NO	34 // 5	168	-233'	241;32	171;32	-21'	171;53
7	6311//-490AP	135 // 20	324;40	-206'	38;07,30	328;07,30	1,5'	328;06
9	7655//-382DE	56 // 8	203;07	-235'	274;36	204;36	-46'	205;22
10	7661//-381JN	170 // 25	16;11	-123'	88;30	18;30	16'	18;14
11	7667//-381DE	49 // 7	192	-133'	263;32	193;32	19'	194;13
30	9903//-200SE	233 // 34	111;13	12'	180;28	110;28	-33'	111;01
31	9909//-199MR	112 // 16	290;19	12'	0;15	290;15	8'	290;07
32	9915//-199SE	226 // 33	100;21	12'	169;24	99;24	-45'	100;09
33	10232//-173AP	139 // 20	330;38	23'	39;52,30	329;52,30	-14,5'	330;07
39	10578//-145AP	133 //19	321;45	52'	30;37,30	320;37,30	-15,5'	320;53
42	10637//-140JA	79 // 11	239;31	58'	307;32	237;32	-61'	238;33
43	10713//-134MR	113 // 16	291;50	60'	0;52,30;	290;52,30	2,5'	290;50
54	13917//125AP	124 // 17	308;24	256'	13;45	303;45	- 23'	304;08
63	14017//133MY	144 // 20	338;03	258'	43;15	333;15	-30'	333;45
69	14035//134OC	16 // 1	139;32	279'	204;12	134;12	-41'	134;53
73	14052//136MR	104 //14	278;13	270'	343;08	273;08	-35'	273;43

4.1: *The Full Moon Zig-zag* in Col. E, latitude, draconitic longitude and eclipse magnitude

But for all that, both Babylonian and Hellenistic astronomy succeeded in building an extremely accurate long-range doctrine of astronomy with a draconitic versus synodic period relation as their common foundation stone:

$$5458 \text{ Ms} = 465 \text{ draconitic years} = 5923 \text{ draconitic months} \qquad (7)$$

Compared to modern standards the resulting motion shows an "error drift" of only 1,6'/century, and Ptolemy's attempt to correct the rate makes no improvement (KPM: 2010, p. 13). With reference to the Full Moon Serpent we found in section 2 that the sun passed about 2275/804 knot intervals per month. By equation (7) this may be finetuned to 5458*2275/804 ≈ 15444, or 7722/2729 intervals per month:

$$(3 - 465/2729)/\text{Ms and } (38 - 465/2729)/\text{Ms for sun and moon respectively} \qquad (8)$$

The ratio 465/2729 counts 465 eclipse warnings during 2729 months, and its continued fraction convergents are obvious candidates for historically important ratios:

1/5, 1/6, 7/41, 8/47, 15/88, 23/135, 38/223, 61/358, 465/2729 (8a)

The well-known Saros period of 223 months plays a key role in *timing* eclipses, and below we shall meet the periods of 6 and 47 months as important building blocks for *locating* eclipses.

Locating full moons in the Serpent, or in the corresponding Babylonian Zig-zag of Col. E, determines: (1) longitudes by way of the nearmost knot number + the longitudinal distance from the knot in question, (2) latitude as the perpendicular distances from the ecliptic, and (3) eclipse magnitudes as derived from the "skew" distance to the knot, provided that the full moon in question is close enough to be eclipsed (KPM:1980, p. 73).

21 lunar eclipses in *Almagest*				Babylonian column E			NASA	
No.	Time GN//YearMM	Place n//N	Magni- -tude	Anomaly col. B	Zig-zag ph. Col. E*	Magnitude	Magni- -tude	Devi- -ation
1	3465//-720MR	111 // 17	Total	185;37,30	23;51,44	lal lal 20,4	18,3	2,1
2	3477//-719MR	104 // 16	3 S +	175;08	22;45,23,12	lal lal 4,3	1,3	3
3	3483//-719SE	218 // 33	>6 N +	344;04	46;58,46,48	u u 7,5	5,9	1,6
4	4703//-620AP	133 // 20	3 S -	216;52,30	1;17,50,48	lal u 3,5	1,8	-1,7
5	5918//-522JL	188 // 28	6 N -	297	25;00,59,48	u lal 7,6	6,4	-1,2
6	6182//-501NO	34 // 5	3 S -	61;32	1;18,34,12	lal u 3,3	2,3	-1
7	6311//-490AP	135 // 20	2 S -	218;07,30	1;30,20	lal u 0,4	1,1	0,7
9	7655//-382DE	56 // 8	Small(-)	94;36	25;27,10	u lal 1,2	2,5	1,3
10	7661//-381JN	170 // 25	3 hrs. (-)	268;30	1;00,40,36	lal u 7,6	5,8	-1,8
11	7667//-381DE	49 // 7	Total	83;32	24;25,25,12	u lal 16,2	17,7	1,5
30	9903//-200SE	233 // 34	3 hrs. (-)	0;28	0;47,46,48	lal u 10,8	8,7	-2,1
31	9909//-199MR	112 // 16	Total	180;15	23;34,22,24	lal lal 16,2	16,6	-0,4
32	9915//-199SE	226 // 33	Total	349;24	47;46,02	u u 19,0	19,1	-0,1
33	10232//-173AP	139 // 20	7 N +	219;52,30	46;52,20,12	u u 5,9	7,4	1,5
39	10578//-145AP	133 //19	Total	210;37,30	23;53,15,48	lal lal 20,8	20,7	0,1
42	10637//-140JA	79 // 11	3 S +	127;32	22;39,07,12	lal lal 2,7	3,1	-0,4
43	10713//-134MR	113 // 16	Total	180;52,30	47;40,36,48	u u 17,7	18,8	-1,1
54	13917//125AP	124 // 17	2 S -	193;45	1;12,51,12	lal u 4,7	1,7	-3
63	14017//133MY	144 // 20	Total	223;15	24;24,31,12	u lal 16,5	12,8	-3,7
69	14035//134OC	16 // 1	10 N +	24;12	47;11,30	u u 10,6	9,9	0,7
73	14052//136MR	104 //14	6 N -	163;08	25;07,08,12	u lal 6,1	5,2	-0,9

The scheme evaluate the reported magnitudes of the *Almagest* eclipses also characterized by lower (S) or upper (N) rim of the moon eclipsed, before (-) or after (+) the nearby node of the lunar orbit, see figure 5. A similar classification turns up in the Babylonian col. E, where the former "lal" or "u" means *above or below* the eclipctic, and the latter "lal" or"u" means on its *way up or down.* For comparison modern reference magnitudes are drawn from NASA's *Five Millennium Catalog of Lunar Eclipses* multiplying the Catalog entries by 12. In the next section we shall explain how the comparable magnitudes of the blue column are embedded in the Babylonian col. E. Their deviations from the NASA entries evolve into:

Dev.(GN) = (7876 – GN)/3886 +/- 1,5 (9)

i.e. drifting by minus one unit per 3 centuries from zero sometime in the 4^{th} century B.C. and keeping the residual variations within an interval of 3 units. One unit of magnitude goes with 2,5' in latitude and about 0,5° in draconitic longitude (or 4' in longitude from the nearby knot). I find this an impressive result for a theory built exclusively on counting lunations and with no mention whatsoevcer of lunar anomaly (KPM:1980, p. 58-60).

As for the *Almagest* reports of eclipse magnitudes 7 entries just tell, that the eclipses were total. Among the remaining, one is called "small" and the durations for two others are given as "3 hours". I equate these notions with magnitudes 2 and 9 respectively (KPM:1980, p. 79). Thus the 14 deviations between *Almagest* and NASA show no drifting, and their average becomes: -0.3 +/- 1,1 i.e. they hit closer than the col. E values. This is of course natural for genuine reports of observation as compared to the col. E theory.

<u>4.2: *The Full Moon Zig-zag*, how to calculate eclipse magnitudes</u>

Traditionally col. E is held to carry lunar latitudes and to produce eclipse warnings near the nodes of the lunar orbit. However, the Babylonians may well instead have investigated eclipse warnings by way of the 35 quasistationary eclipsing "knots" spread along the Full Moon Serpent, cf. Equation (4). Clearly a Babylonian "serpent" should show zig-zags instead of sinusoidal "waves". As seen in Fig. 6 the distance from a "knot" (at 0°) reaches a maximum of 12°, whence it decreases via the next following "knot" to a minimum of -12°. Finally it goes up to the third "knot" completing a full zig-zag of wavelength 48°. After 17,5 zig-zags making a full revolution another (red) wave begins at 0°, but shifted by half a wavelength. By hindsight we know that this reflects a shift between the lunar nodes.

Clearly the "distance" between a "knot" and the full moon can never reach 12°. But Col. E yields sound results by halving whatever goes beyond 2,4°. So you get the maximum distance of 7,2° as in the text and in perfect agreement with a maximum full moon latitude of 5°. Zig-zag phases and "knot" distances are correlated as given below:

x° in Zig-zag	0°-12°	12°-24°	24°-36°	36°-48°
text distance	x° lal u	(24-x)° lal lal	(x-24)° u lal	(48-x)° u u

So far we may count during any relevant period *(a) revolutions*, each comprising 17,5 full Zig-zags, *(b) additional Zig-zags,* each comprising two knot distances, and *(c) the fraction of the last wave passed by the full moon.*

We may, however, as well think of *the full moon phase in any zig-zag, ph*, as strongly dependent on the full moon longitude, given in col. B, but with a small correction dependent on time, i.e. the lunation number GN:

ph(B, GN) = fraction of {(2761/96 – B – 3757*GN/2400)/360} (10)

The midle term, B/360, reflects automatically the inequality due to solar anomaly, and the last term (by hindsight) goes with the monthly drift of the lunar nodes. Now multiplication by 48, the effective zig-zag "wavelength", creates the actual col. E values,

$$x = 2761/720 - 2*B/15 - 3757*GN/18000 + q*48, \quad 0 \le x \le 48 \quad (11)$$

This produces rather reliable lunar eclipse magnitudes, which compare favourably with NASA's Canon, cf. Equation (9). That is so because the unequal motion of *the slow sun locates correctly, where* full moons may occur. The inequality of lunar motion enters the scene mostly in timing the penomena. A full moon event happens, *when the swift moon* arrives at the correct position.

To compare eclipse magnitudes inherent in Col. E with Greek (and modern) standards we used the correlations:

Maximum eclipse, *magnitude 22,4*, is a central eclipse, *distance 0 from knot.*
Smallest total eclipse, *magnitude 12*, occurs near the *distance 0;43 from knot*
Limit of eclipse occurrence, *magnitude 0*, goes with *distance 1;32 from knot*
Penumbral eclipses, invisible to the naked eye, are given *negative magnitudes*

4.3: *The Full Moon Zig-zag*, useful selections of lunar eclipses

In order to select possible eclipses, say among the 235 full moons in Figure 1, i.e. *from GN 6580 (-468 JA) through GN 6814 (-450DE)*, you may begin noting that eclipses occur at six months intervals. Below partial and total eclipses are shaded in light grey and grey respectively:

GN 6580, 6581, 6582, ... 6586, 6587, 6588, ... 6592, 6593, 6594, ... etc.

After five or six eclipses you meet an interval of 11 or 17 months, because a five month interval has crept into the series. However, after 7*6 + 5 = 47 months a new row of eclipses 6 months apart appears,

GN 6627, 6628, 6629, ... 6633, 6634, 6635, ... 6639, 6640, 6641, ... etc.
GN 6674, 6675, 6676, ... 6680, 6681, 6682, ... 6686, 6687, 6688, ... etc.
GN 6721, 6722, 6723, ... 6727, 6728, 6729, ... 6733, 6734, 6735, ... etc.
GN 6768, 6769, 6770, ... 6774, 6775, 6776, ... 6780, 6781, 6782, ..etc.. 6813, *6814.*

Note that these 47-month rows imitate the five 47-month turns of a spiral found on a dial at the back of the so-called Antikythera gear mechanism. Perhaps it is worth examining whether or not the shaded eclipse columns are traceable on the machine (Freeth et al.2006, KPM:2010, appendix A).

Anyway all potential lunar eclipses are to be found among the 40 full moons with GN belonging to the five-by-eight matrix in the following table, and with six (or five) month intervals in the horizontal rows and 47 month intervals in the columns. For the most accurate eclipse information we refer to *NASA's Five Millennium Catalog of Lunar Eclipses.* Among the 235 full moons under examination NASA lists 12 total and 17 partial eclipses accentuated here by grey and pale grey background respectively. In addition NASA has 16 eclipses, here on yellow background. They are penumbral and accordingly invisible in pretelescopic astronomy. Nevertheless, all of the 29 real eclipses, visible somewhere on the Earth, and 11 out of the 16 penumbral ones are caught in the five-by-eight matrix.

N = 0, 7, 14,21,28	N = 3, 10, 17,24,31	N = 6, 13, 20, 27, 34	N = 2, 9, 16,23,30	N = 5, 12, 19,26,33	Five month interval N = 1, 8, 15, 22, 29		N = 4, 11, 18, 25, 32
6581	6587	6593	6599	6605	6611	6616	6622
6628	6634	6640	6646	6652	6658	6663	6669
6675	6681	6687	6693	6699	6705	6710	6716
6722	6728	6734	6740	6746	6752	6757	6763
6769	6775	6781	6787	6793	6799	6804	6810
6623				6704			6617
							6664
							6758

Coming to eclipse positions, say by knot number, the two columns five months apart coalesce into one, and we end up with a 5 by 7 matrix producing an entry (single or double) for each of the 35 knots. The overwhelming majority of the single entries make eclipses, whereas only few components of the double entries go with eclipses.

Eclipse positions 469 to 451 BC by knot and step nos.							
14 95	**31** 209	**13** 88	**30** 202	**12** 81	**29** 195	**8** 55	**25** 169
7 48	**24** 162	**6** 41	**23** 155	**5** 34	**22** *148*	**1** 8	**18** 122
0 1	**17** 115	**34** 229	**16** 108	**33** 222	**15** 101	**29** 196	**11** 75
28 189	**10** 68	**27** 182	**9** 61	**26** 175	**8** 54	**22** *149*	**4** 28
21 142	**3** 21	**20** 135	**2** 14	**19** 128	**1** 7	**15** 102	**32** 216

According to equation (8) the sun passes (3 - 465/2729) knot intervals pr. Ms and with f of equation (1) equal to 349/2729 we get:

(14 + 404/2729) intervals during 5 Ms; (404/2729 - f)*180° = 3;38°
(385 - 473/2729) intervals during 136 Ms: (473/2729 - f)*180° = 8;11°
(280 + 358/2729) intervals during 99 Ms; (358/2729 - f)*180° = 0;36°,

where the right hand arcs denote the surplus angle over the total eclipse warning interval. So the periods of 5, 99, or 136 months cannot enjoy eclipses at both ends; but they may well *avoid* eclipses at both ends with an eclipsing knot in between, as seen e.g. in the scheme at knot 22. Here the two full moons 99 months apart must needs be almost symmetrically located before and after the knot.

To investigate the overall reliability of the Babylonian eclipse data the following scheme repeats our 5 by 7 matrix identifying each entry by GN and knot numbers. Then follows year, month and eclipse magnitudes drawn from the NASA eclipse catalog with total, partial and penumbral eclipses on grey, light grey and yellow background respectively. Next come eclipse type and magnitude as calculated above from Babylonian Column E. Finally you find the deviations on pale blue background.

Col. E predicts all of the actual eclipses and in addition two penumbral eclipses of very small (negative) magnitude, viz. - 1,3 and - 0,6. And it classifies the eclipses correctly apart from GN 6699 where Col. E leads to a total eclipse, instead of a partial, magnitude 9,8. For the 29 actual eclipses the deviations on the average come out as 0,4 +/- 1,4 in full agreement with equation (9), Dev.(6700) = 0,3.

N = 0, 7, 14, 21, 28	N = 3, 10, 17, 24, 31	N = 6, 13, 20, 27, 34	N = 2, 9, 16, 23, 30	N = 5, 12, 19, 26, 33	N = 1, 8, 15, 22, 29 I	II	N = 4, 11, 18, 25, 32
6581/14	**6587/31**	**6593/13**	**6599/30**	**6605/12**	**6611/29**	**6616/08**	**6622/25**
-468FE/5,1	-468AU/1,9	-467FE/20,8	-467AU/18,2	-466JA/8,6	-466JL/9,3	-466DE/-11,9	-465JN/-4,7
lal u 4,2	u lal 3,0	lal u 18,9	u lal 19,0	u u 10,4	lal lal 9,0	lal u -11,8	u lal -5,5
0,9	-1,1	1,9	-0,8	1,8	-0,3	-0,1	0,8
6628/07	**6634/24**	**6640/06**	**6646/23**	**6652/05**	**6658/22**	**6663/01**	**6669/18**
-465DE/2,1	-464JN/11,3	-464NO/17,5	-463MY/17,0	-463NO/11,2	-462MY/-1,3	-462OC/-10.9	-461AP/-0,6
lal u 2,9	u lal 10,5	lal u 17,6	lal lal 17,5	u u 11,7	lal lal 1,5	lal u -13,2	u lal 2,0
-0,8	0,8	-0,1	0,5	0,5	2,8	2,3	-2,6
6675/00	**6681/17**	**6687/34**	**6693/16**	**6699/33**	**6705/15**	**6710/29**	**6716/11**
-461SE/3,0	-460MR/16,8	-460SE/17,9	-459MR/11,2	-459SE/9,8	-458MR/-3,7	-458AU/-6,0	-457JA/5,6
lal u 1,5	u lal 18,0	lal u 16,2	lal lal 10,0	u u 13,0	lal lal -4,8	lal u -10,0	u lal 3,7
1,5	-1,2	1,7	-1,2	3,2	-1,1	4	1,9
6722/28	**6728/10**	**6734/27**	**6740/09**	**6746/26**	**6752/08**	**6757/22**	**6763/04**
-457JL/4,6	-456JA/20,6	-456JL/22,0	-456DE/7,5	-455JN/7,1	-455DE/-7,0	-454MY/-2,4	-454NO/2,3
lal u 6,0	u lal 18,4	u u 22,0	lal lal 10,9	u u 6,0	lal lal -3,5	lal u -2,5	u lal 4,4
-1,4	2,2	0	3,4	-1,1	3,5	0,1	-2,1
6769/21	**6775/03**	**6781/20**	**6787/02**	**6793/19**	**6799/01**	**6804/15**	**6810/32**
-453MY/13,6	-453OC/17,9	-452AP/13,5	-452OC/12,1	-451AP/-2,6	-451OC/-4,4	-450MR/4,3	-450AU/0,7
lal u 13,5	u lal 16,8	u u 14,5	lal lal 12,5	u u -1,6	lal lal -2,2	lal u 4,0	u lal 1,5
0,1	1,1	1	0,4	1	2,2	0,3	-0,8

5: *Strings of beads:* long range control of lunar eclipses

So far we have established correspondence between Babylonian column E and lunar eclipse data, including utterly sensitive eclipse magnitudes. The connection deals with both annual variations and stability over centuries. Now between observations and tables you must stick to a one-way route. Reliable eclipse data cannot possibly result from column E, unless this column was first calibrated by eclipse observations. We have followed one possible route to full column E calibration, but neither by necessity the only possible way, nor the actual path traced by ancient astronomers. Here follows a resumé of the argument until the final step, viz. that of long range calibration.

We chose numbering consecutive full moons as the natural time measure in lunar eclipse astronomy, *ancient ephemeris time*. And we learned to locate eclipses in the zodiac by way of a *full moon serpent* of 235 steps, and with 35 eclipsing knots of intersection. At each knot eclipses occur in triads, with 235 months between the eclipses, and with the knots themselves drifting to the next step during 804 months = (65+1/235) years. The move of one step pr. 65 years, or 2;21°/century, surpasses considerably the directly observable drift of eclipse locations among the stars. So you are led to accept an increase of stellar longitude, or *precession*, of 1°/century. During 804 months the sun passes 65*35 = 2275 knot distances, and the monthly change of "knot phase" is 2275/804 = 3 – 137/804, equivalent to the monthly draconitic motion of the sun of (137/804)*180° ≈ 30;40,18°/Ms, 4" above the mark.

The annual inequality of the relative motion between the luminaries produces a directly observable uneven distribution of the 35 eclipsing knots. Column B of Babylonian system A "solar" ephemerides imitates closely the actual orbital motion, (225/2783)*360° ≈ 29;06,19°/Ms, 1" pr. 4 months below the (anomalistic!) mark.

We have seen that combining the unequal distribution of eclipses in the zodiac, governed by 225 years = 2783 Ms, with the long term drift, based upon 465 draconitic "half-years" = 2729 Ms, paved the way for deriving eclipse magnitudes that compare favourably with modern standards. How did the draconitic solar motion, (465/2729)*180°/Ms = ***30;40,14,04°/Ms*** , come out of eclipse observations, above the mark by trifling 1" pr. 15 months? This must needs involve observations over a prolonged span of time.

During any period of 47 months the draconitic motion of the sun on the average comes close to 8 half-revolutions plus 1,5°. So it takes 23/1,5 = 15 periods, or 57 years, to pass the nodal zone, and about <u>180/1,5 = 120 periods</u>, or 4,5 centuries, to move an extra half-revolution and enter the opposite nodal zone. This means that after 60 years with eclipses like a string of beads, total eclipses in the middle and partial ones of decreasing magnitudes towards both ends, there follow four centuries without any eclipses.

In the serpent, or zigzag, picture the eclipse strings continue the columns of our 5 by 7 matrix and combine 5 triads at the knots forming a pentagon. And during four eclipse free centuries the full moons creep across a knot distance, up along a "zig" and down along a "zag", to the neighbouring pentagon corners.

Now each of the continued fraction convergents to the final solution, 465 eclipse warnings during 2729 months, goes with its own number of 47 month periods necessary to cover 180°:

	47•23/135 = 8 + 1/135		far above
	47•38/223 = 8 + 2/223	1/111,5	far below, (NB: Saros cycle)
sum	47•61/358 = 8 + 3/358	1/119,3	close

the next convergent must fall between the two latter solutions by way of an interval of the form 223 + q•358. The q-values 6, 7 and 8 prove relevant in history and astronomy:

q = 6,	47•404/2371 = 8 + 1/118,55 ≈ 1/(118+1/2)	*Almagest* (?)
q = 7,	47•465/2729 = 8 + 1/118,65 ≈ 1/(118+2/3)	Babylonian col. E
q = 8,	47•526/3087 = 8 + 1/118,73	Modern reference

Now the period between Nabonassar's Epoch in mid eighth century B.C. and Ptolemy's flourish in mid second century A.D. covers 9 centuries, or two full intervals between eclipse strings. And indeed, as seen in the following scheme the *Almagest* selection of 21 lunar eclipses includes two pairs connected by 47 months intervals, nos. 2 & 73 and nos. 3 & 54, and accordingly apt for *long range determination of the draconitic drift around the beginning of the Seleucid Era*, and again for a check up by Ptolemy.

21 lunar eclipses in *Almagest*

No.	Time GN//YearMM	Place n//N	Magni- -tude	Rem.	GN=p*47+r p//r	LRC Δp
1	3465//-720MR	111 // 17	Total	Bab. A'	73//34	
2	3477//-719MR	104 // 16	3 S +	Bab. A'	**- - //46**	**X**
3	3483//-719SE	218 // 33	>6 N +	Bab. A'	**74//05**	**Y**
4	4703//-620AP	133 // 20	3 S -	1°/cent.	**100//03**	**Z**
5	5918//-522JL	188 // 28	6 N -		125//43	
6	6182//-501NO	34 // 5	3 S -	Hipp.	131//25	
7	6311//-490AP	135 // 20	2 S -	1°/cent.	134//13	
9	7655//-382DE	56 // 8	Small(-)		162//41	
10	7661//-381JN	170 // 25	3 hrs. (-)		163//00	
11	7667//-381DE	49 // 7	Total	Hipp.	- - - //06	
30	9903//-200SE	233 // 34	3 hrs. (-)		***210//33***	
31	9909//-199MR	112 // 16	Total		- - - //39	
32	9915//-199SE	226 // 33	Total		- - - //45	
33	10232//-173AP	139 // 20	7 N +	1°/cent.	***217//33***	
39	10578//-145AP	133 //19	Total		**225//03**	**Z+125**
42	10637//-140JA	79 // 11	3 S +		226//15	
43	10713//-134MR	113 // 16	Total		227//44	
54	13917//125AP	124 // 17	2 S -		**296//05**	**Y+222**
63	14017//133MY	144 // 20	Total	1°/cent.	298//11	
69	14035//134OC	16 // 1	10 N +		- - - //29	
73	14052//136MR	104 //14	6 N -		**- - - //46**	**X+225**

E.g. with reference to the calculation above an observed number of 47 month periods *"between 118 and 119, but closer to the latter"* could result in the chosen value 118+2/3, which again could be corroborated say by Hipparchus, or some UHA (Unidentified Hellenistic Astronomer), comparing the eclipses nos. 4 and 39.

Ptolemy, on the other hand, could from eclipse no. 3 ending a string of eclipses, GN 3483, to no. 54 initiating another string, GN 13917, count 222•47 months, which together with the 14•47 months of an entire string makes 236, or two times 118. So this could motivate what he might believe to be an improvement over the Babylonian solution. He told, however, quite another story about the genesis of his correcting the

Babylonin value for the draconitic rate of motion. And after all many different selections of eclipse data may have contributed to the Col. E calibration.

Anyway to illustrate further the correspondence of Column E and lunar eclipse observations and at the same time the predictive power of this column I have put together in tables the eclipse series suggested by the scheme above:

1: The three sets with GN = p•47+5 around 750 BC, 300 BC, and AD150, all supplemented by a modern check up string about AD 1950.
2: The three sets with GN = p•47+ 46 around 750 BC, 300 BC, and AD150.
3: The two sets with GN = p•47+3 around 600 BC and 150 BC.

Each set is really like a string of beads with total eclipses in the middle and partial ones towards both ends. But distributed among the corners of their pentagon the change of magnitude is anything but linear. Anyway the col. E results follow the NASA standard rather closely. This is obvious from the said tables and further illustrated in Fig. 7 with the first set of pentagonal string members marked in blue and put together as if they occurred at the same "knot". After the series of 15 eclipses between -772JN and -719SE (*Almagest* no. 3) full moons at 47 months intervals continue to creep down along the "u u" zig-zag branch to the bottom at 36° (see Fig. 6), and up again along the "u lal" branch where you find another eclipse series from -327JA through -267NO marked in magenta in Fig. 7. Finally after another pause of almost 400 years the *Almagest* eclipse no. 54 initiates the third string of 15 eclipses.

The NASA magnitudes in the tables are classified by N or S (in red) to signify whether the northern or the southern rim of the moon is eclipsed. For eclipses marked by "lal lal" or "u u" the deviations are found as col.E magnitude minus NASA magnitude, while the "lal u" or "u lal" deviations result as NASA magnitude minus col. E magnitude. For GN4985 the combination of "lal u" and N means that the descending node of the lunar orbit falls in between, and the deviation is 2•22,4 – 22,1 – 19,4 = 3,3.

Similarly with the combination of "u u" and S in the last scheme for 20th century data, e.g. for GN36618 we get the deviation 17,7 + 17,1 – 2•22,4 = -10. The average deviation of -9,4 +/- 1,5 shows the same spread as the strings from Antiquity. So the effect of annual anomaly has not been ruined by the accumulated error of about 3° in apsidal longitude. And all the average string deviations dealt with decrease from 0 about 300 BC by 4 units of magnitude pr. millennium:

Av. Dev. = (8715 – GN)/3069. (12)

<u>6: *The New Moon Zig-zag*, and solar eclipses</u>

With the col. E calibration firmly established by way of lunar eclipse observations the same column for half integral GN-numbers by analogy yields information about New Moons, in particular forecasting the occurrence anywhere on the Earth of solar eclipses.

Here follow examples of solar eclipse warnings, where the "magnitudes" are given both as calculated from Col. E and as corrected by the deviation of equation (12). Of course solar eclipses do not show "magnitudes" like lunar ones, but the numbers reflect new moon latitudes which in their turn affect the geographical locations hit by the eclipses.

Time GN//YearMM	"Longitude" Equ. 5 & 6	Zig-zag phase X of equ. 11	"Magnitude"	Reference
5149,5//-584MY	71;11,15	23;31,40,42	lal lal 15,5//14,3	Thales
17479,5//413AP	21;03,45	0;39,58,42	lal u 12,7//9,8	"Golden Horns"
37099,5//1999AU	103;48,45	22;33,10,42	lal lal 0,6//11,5	Le Havre obs.

The first eclipse is said to have been predicted by Thales, the second was possibly observed in southern Jutland and dealt with in cryptic runes inscribed at the Long Golden Horn of Gallehus (W. Hartner:1969), and my family observed the last solar eclipse before 2000 entering the European continent at the beach of Le Havre and thus inaugurating the wedded blis of our young French/Danish couple.

Time GN//YearMM	**Longitude** Equ. 5 & 6	**Zig-z. Phase** X of equ. 11	**Lati- tude**	**Remark**
9996.5//-192AP	26;03,45	25;52,04,54	-1;41	Partial S
10043,5//-188FE	313;44	25;42,07,06	-1;32	Partial S
10090,5//-185NO	239;28	25;52,04,54	-1;37	Partial S
10137,5//-181SE	165;12	25;52,04,54	-1;42	Partial S
10184,5//-177JN	95;26,15	25;22,41,42	-1;01	Total
10231,5//-173AP	25;48,45	24;51,05,54	-0,46	Annular
10278.5//-169FE	313;28	24;41,16,06	-0;37	Hybrid
10325,5//-166NO	239;08	24;47,20,18	-0;43	Total
10372,5//-162SE	164;56	24;52,20,30	-0;47	Annular
10419,5//-158JN	95;11,15	24;21,42,42	-0;20	Hybrid
10466,5//-154AP	25;33,45	23;50,06,54	+0;09	Hybrid
10513,5//-150FE	313;12	23;40,25,06	+0;18	Annular
10560,5//-147NO	238;52	23;46,29,18	+0;12	Total
10607,5//-143SE	164;40	23;51,29,30	+0;08	Annular
10654,5//-139JN	94;56,15	23;20,43,42	+0;35	Hybrid
10701,5//-135AP	25;18,45	22;49,07,54	+1;04	Total
10748,5//-131FE	312;56	22;39,34,06	+1;12	Annular
10795,5//-128NO	238;36	22;45,38,18	+1;07	Total
10842,5//-124SE	164;24	22;50,38,30	+1;02	Annular
10889,5//-120JN	94;41,15	22;23,44,42	+1;27	Partial N
10936,5//-116AP	25;03,45	21;48,08,54	+1;59	Partial N
- - -				- - -
11077,5//-105SE	164;08	21;49,47,30	+1;57	Partial N

String of solar eclipses with GN = 32,5 + p•47 including GN 10701,5 observed in Babylon (KPM:1987, p.52).

This scheme offers an overwiev of solar eclipses in the string with GN = 32,5 + p•47. At both ends you meet "partial" eclipses in the Antarctic and the Arctic where the shadow cone apex aims “below” and “above” the South and North pole respectively. In between you find 15 “ordinary” string members crossing the Earth from South to North according to the change in latitude. This is further iilustrated by modern eclipse sketches in Fig. 8, copied from (Espenak & Meeus: 2006). They are classified “total” or “annular” according to whether the shadow cone apex is found below or above the surface of the Earth. The “hybrid” eclipses shift between the “total” and “annular” situations.

With reference to Fig. 6 the “Zig-zag” slope close to an eclipsing knot is found as Arccos(5,2/12) = 64,3°. So the new moon latitudes are found as the distance from the knot multiplied by sin64,3°, positive or negative at the “lal lal” or the “u lal” branches respectively.

Now solar eclipses are rare events in definite geographical regions. So ancient astronomers could never build systematic knowledge based on solar eclipse data. But the rules and periodicities unveiled above for full moons and in paticular lunar eclipses set the pattern for similar new moon and solar eclipse regularities. And, indeed, when eventually the sun was eclipsed, it did allways happen at an expected syzygy. But only a tiny minority of the possibly expected eclipses did actually come out, whence the repeated remarks in the Babylonian diaries: “... solar eclipse which was omitted ...” or “...solar eclipse, I did not see it ...”. This may have caused wonder. Or it may have brought reputation to the court astrologers for their ability to predict eclipses, but even more because they ordinarily succeded in turning an eclipse of the sun into a partial eclipse or in flatly preventing it from coming up. Just imagine the triumph of the profession when a traveller from far away could report the event of a total solar eclipse exactly at the time they had predicted. Not only had their prayers kept their own king free from this “bad omen”, but the evil had been directed against a foreign king and country. Time for regulation of salary !

<u>7: Planetary tables out of eclipses ?</u>

Babylonian planetary ephemerides list consecutive occurrences of specific synodic phenomena, say the first stationary point of Jupiter. The tables then give, line by line, *dates* by tithis counted within a specified year and month of the Seleucid calendar, and *sidereal positions* by degrees within a specified constellation of the zodiac.

Possibly the ephemerides reflect a praxis of keeping accountance with *sidereal positions for the synodic planetary phenomena.* It appears that rather rough statistics over a few centuries may lead to solid results (Aaboe:1980). So we end up with sidereal period relations, e.g. several variants of Jupiter tables show that during 427 sidereal years Jupiter meets with 391 synodic phenomena and is brought back to the same position among the stars after 36 sidereal revolutions:

$$391\ Ts = 36\ T^* = 427\ A^* \qquad (13)$$

Together with the year to month ratio, $A^* = 2783/225$ Ms, this immediately yields the synodic period counted in tithis:

$$Ts = 427/391 \bullet 2783/225 \bullet 30 = (360 + 45;13,53) \text{ tithis} \qquad (14)$$

whereby the entire backbone of the Jupiter tables is at hand. This is supported by

Babylonian procedure texts.

But you may as well take off from *synodic* relations based on *parallel countings of synodic phenomena of the planet and of the moon*. And this is what we revealed in early greek astronomy finetuning the mean planetary motions by observations of planets close to lunar eclipses (KPM:2010). Returning to Babylon we meet an earlier problematic Jupiter parameter ”13;30,27,46” (O. Neugebauer:1983, p.392). It tells, however, the synodic Jupiter period in months, 13;30,27,46•30 = 405;13,53, and with the year to month ratio, 2783/225, it produces again a complete Jupiter theory.

So far one might suggest that Babylonian and Hellenistic astronomers built planetary tables on sidereal positions and lunar eclipses respectively. However, to get a bird's eye view of the interplay between all these data I prepared the following scheme in two green frames; planetary synodic periods measured by months within the upper, and by sidereal years within the lower frame. Together with any month measure, Ms/Ts, you find, on grey background, the corresponding draconitic motion of the sun, calculated as 465/2729•Ms, i.e, telling the number of draconitic half-revolutions plus the fraction of the next 180°. This facilitates identifying combinations of periods for building observable eclipse intervals.

Saturn		**Jupiter**		**Mars**		**Venus**		**Mercury**	
12<Ts<13	drac.	13<Ts<14	drac.	26<Ts<27	drac.	19<Ts<20	drac.	3<Ts<4	drac.
64/5	10,91			53/2	9,03	178/9	30,33		
717/56	122,17	27/2	4,60	132/5	22,49	435/22	74,12	51/13	8,69
781/61	133,08	878/65	149,60	449/17	76,51	1048/53	178,57	310/79	52,82
1498/117	255,25	905/67	154,21	2377/90	405,02	2531/128	431,26	671/171	114,33
845/66	143,98	2688/199	458,01	581/22	99,00	1661/84	283,02	1291/329	219,98
851/66;28	145,00	<-- 851/63	145,00						
1<A*/Ts<2		1<A*/Ts<2		2<A*/Ts<3		1<A*/Ts<2		0<A*/Ts<1	
				79/37				33/104	
				284/133		**8/5**		**46/145**	
59/57		83/76		363/170		235/147		217/684	
324/313		344/315		647/303		478/299		263/829	
265/256		427/391				980/613		388/1223	

To be sure, all data above the yellow strips are found by hindsight, namely drawn from my tables of reference (KPM:1975) as continued fraction convergents, increasing to the left and decreasing to the right. Each convergent makes for the 'best' approximation, in the sense that no irreducible fraction with a smaller denominator will hit closer than the ratio in question. So above the yellow lines you find the most reliable fractions corresponding to any given limit of accuracy. I have chosen to keep the eclipse periods below a couple of centuries, and the spans of sidereal years under half a millennium, except that 647 years proves necessary for calculating the *Almagest* mean motion table of Mars.

Combining month and year measures for the synodic periods of each planet we get the sidereal year to month ratio involved, e.g. for Saturn (1498/117)/(324/313) = 12;22,07,26.7 Ms/A*, and for all five planets we have the yellow line average:

Average accuracy limit for Ms/A* = 12;22,07,27.3 +/- ..02.2 (15)

You could easily tighten the clearance further, but that would make no sense with reference to observational practice in antquity. Drawn directly from my table of reference the year to month ratio comes out as 12;22,07,30 = 1979/160.

Below the upper yellow strip you find linear combinations of the convergents. Hitting eclipse periods they appear tailor-made for observing planets close to eclipses at both ends. Ratios marked with red background proved instrumental for the calculation of "prototables" behind the *Almagest* mean planetary motions (KPM:2010, pp. 4-12). They came out of continued fraction analysis of the *Almagest* tables as exceptionally close hits covering less than a couple of centuries, and into the bargain as rather good eclipse intervals.

Combination with the year measures also marked in red produces the average:

Average Ms/A* for red entries = 12;22,07,24.9 +/- ..01.5 (16)

Now this number counts Ms(A) = 29;31,50,20 days. But 12;22,07,25•Ms(A) = 12;22,07,30•29;31,50,08,20 = **1979/160•Ms(B)**. So that is how the *Almagest* inconsistency pops up between generally using the System B month, but switching to the System A month when fixing the planetary mean motions (KPM:2010, p. 4). By hindsight we know that Ms(B) hits the mark to within a fraction of a second, and that prototables yielding *monthly* motion were superior to the final tables with *daily* rates of motion (KPM:2010, pp. 9-12). So why not simply use *the ratio 1979/160 of months per sidereal year*. To be sure I have never found this particular ratio in ancient sources. It is equivalent, however, with the year (synodic, tropical, or anomalistic) of 235/19 months, or its finetuned version of (120 + 23/360)/1485 months, in combination with "precession" close to a degree per century:
(19/235 - 160/1979)360•1237 = 57,5' or (43223/1485 – 57600/1979)•1237 = 58,5'.
It is questionable, though, whether or not ancient astronomers were able to decide between the two month measures.

Among the A*/Ts entries on red background we learn, that Saturn and Mars come up with genuine convergents above the yellow strip, and that the Jupiter and Mercury ratios were known to the Babylonians as indicated by white script on coloured background. Thus we are left with problematic(?) Venus which in spite of the period of almost a millennium (980 years) does not hit the same level of accuracy as the other four planets. It could be tempting to come closer by further continued fraction analysis of the desired result: (1661/84)/12;22,07,25 ≈ ..., 243/152 , *980/613*, 2203/1378, ... corresponding to the A*/Ms measures: ..., 12;22,07,41.4, *...,23.4*, ...,25.4, but that demands a still more fantastic period beyond observational and historical relevance of almost two millennia. *Calculational* refinement of data is always possible. But here the relevant historical information hides in the fact that four out five planets do not call for any refinement. What about the Babylonian A*/Ms = 2783/225 = 12;22,08 ? In fact it turns up in relation to the convergents on blue background:

Saturn: (717/56)/(324/313) = 12:22,07,58.6)
Jupiter: (878/65)/(427/391) = ... ,07,56.0)
Mars: (449/17)/(284/133) = ... ,08,00.2)Av. = ... ,08,00.5 +/- 03.7
Venus: (2531/128)/(235/147) = ... ,08,05.9)
Mercury: (310/79)/(217/684) = ... ,08,01.7)

So it might be worth looking for the corresponding period relations in cuneiform source material. One problem remains. For Saturn the clay tablets deal with 265/256 years per synodic revolution instead of the convergent 324/313 also in the list above. Anyway (717/56)/(265/256) = 12;22,07,26.4, compatible with equation (16).

In (KPM:1980) I asked a question: *The Full Moon Serpent. A Foundation Stone of Ancient Astronomy ?* Today after intensive mathematical snake charming I will not hesitate to omit the question mark, noticing only that ancient serpents took the form of Zig-zags !

8: References

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9: Appendix with figures and tables

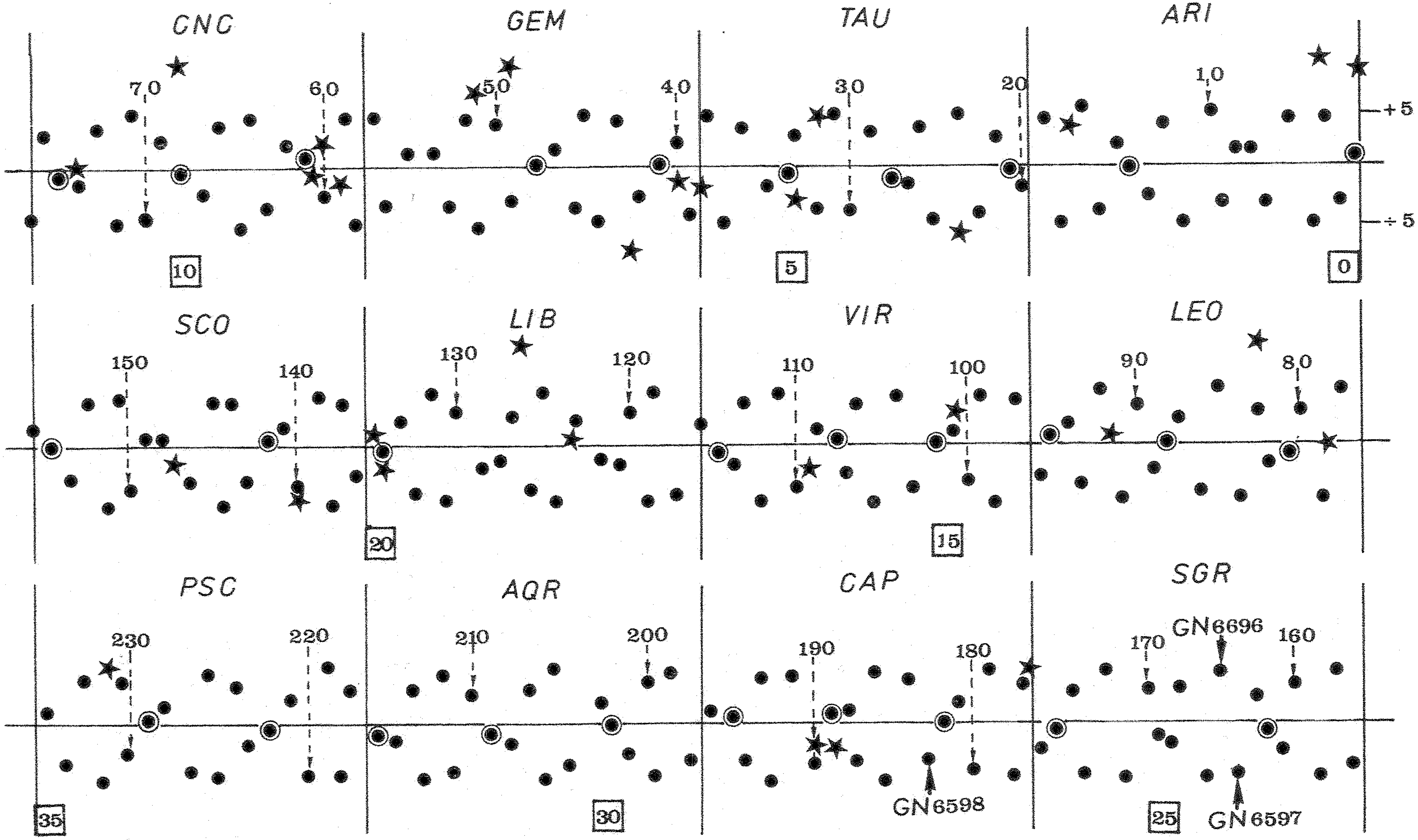


FIG. 1. Map of the zodiac for the epoch 450 B.C., with positions of the 235 Full Moons from 469 to 451 B.C. Lunar eclipses are marked by circles around the Full Moon dots.

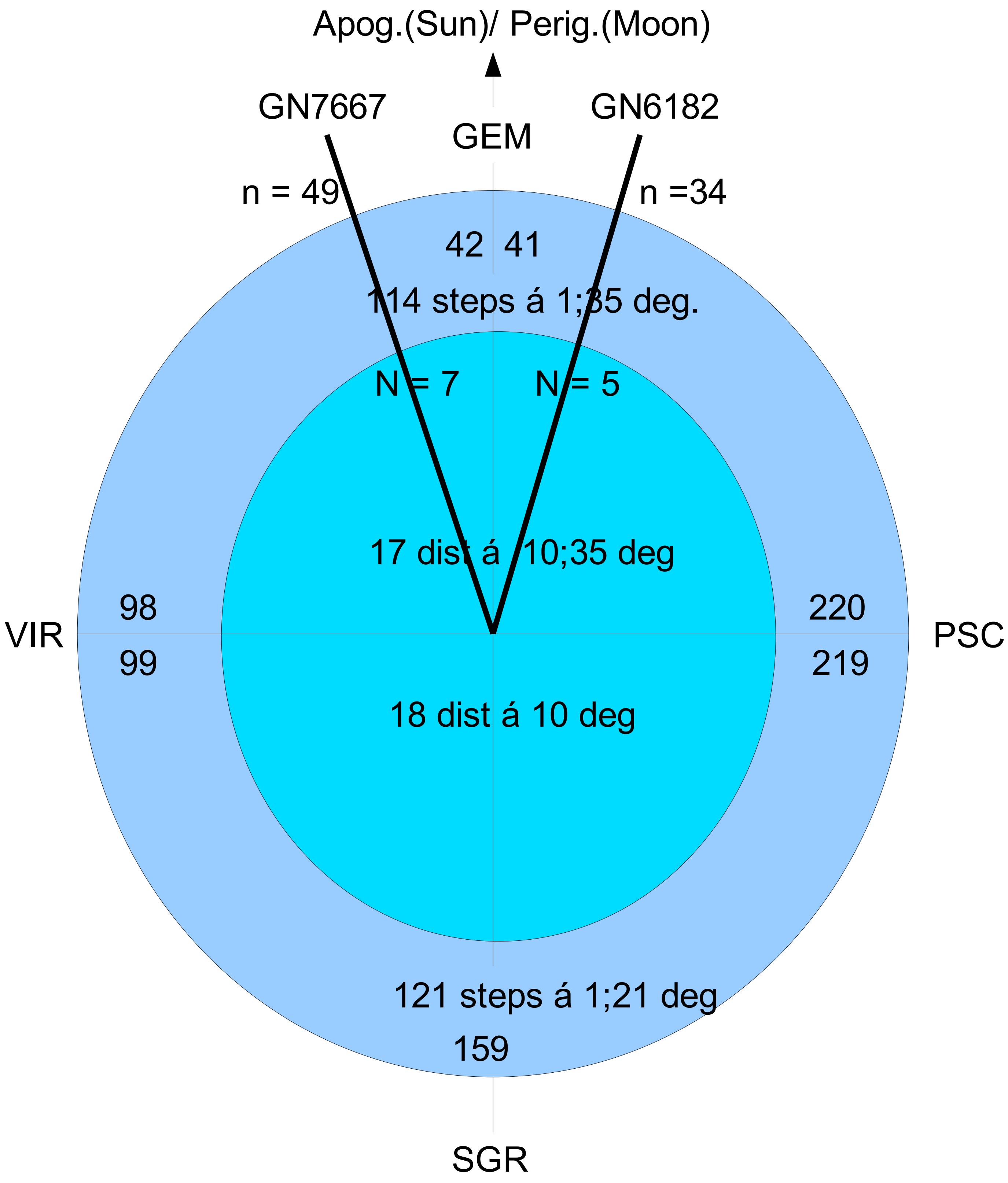


Figure 2: m-steps and eclipse distances in their skew distribution around the Zodiac

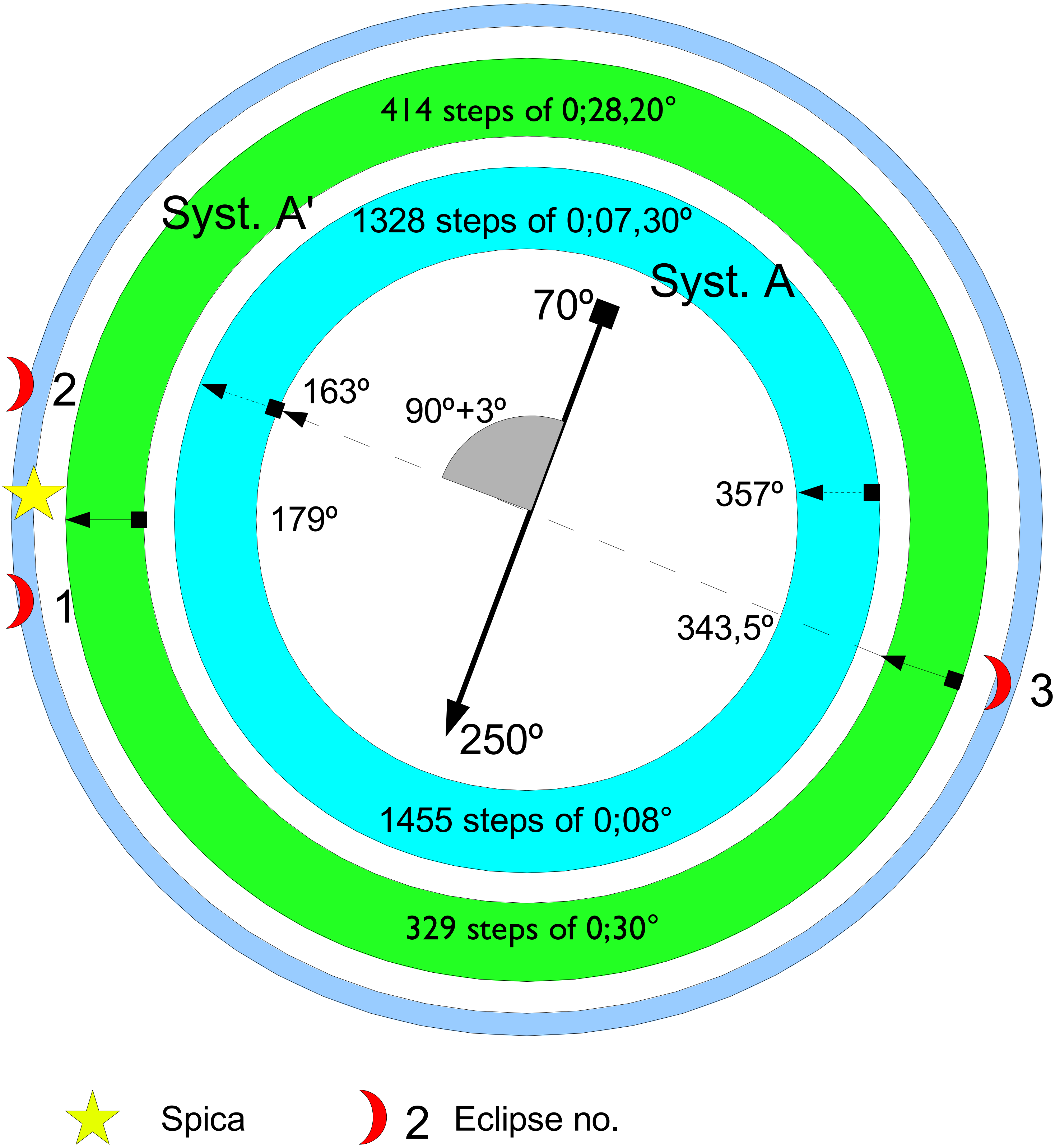
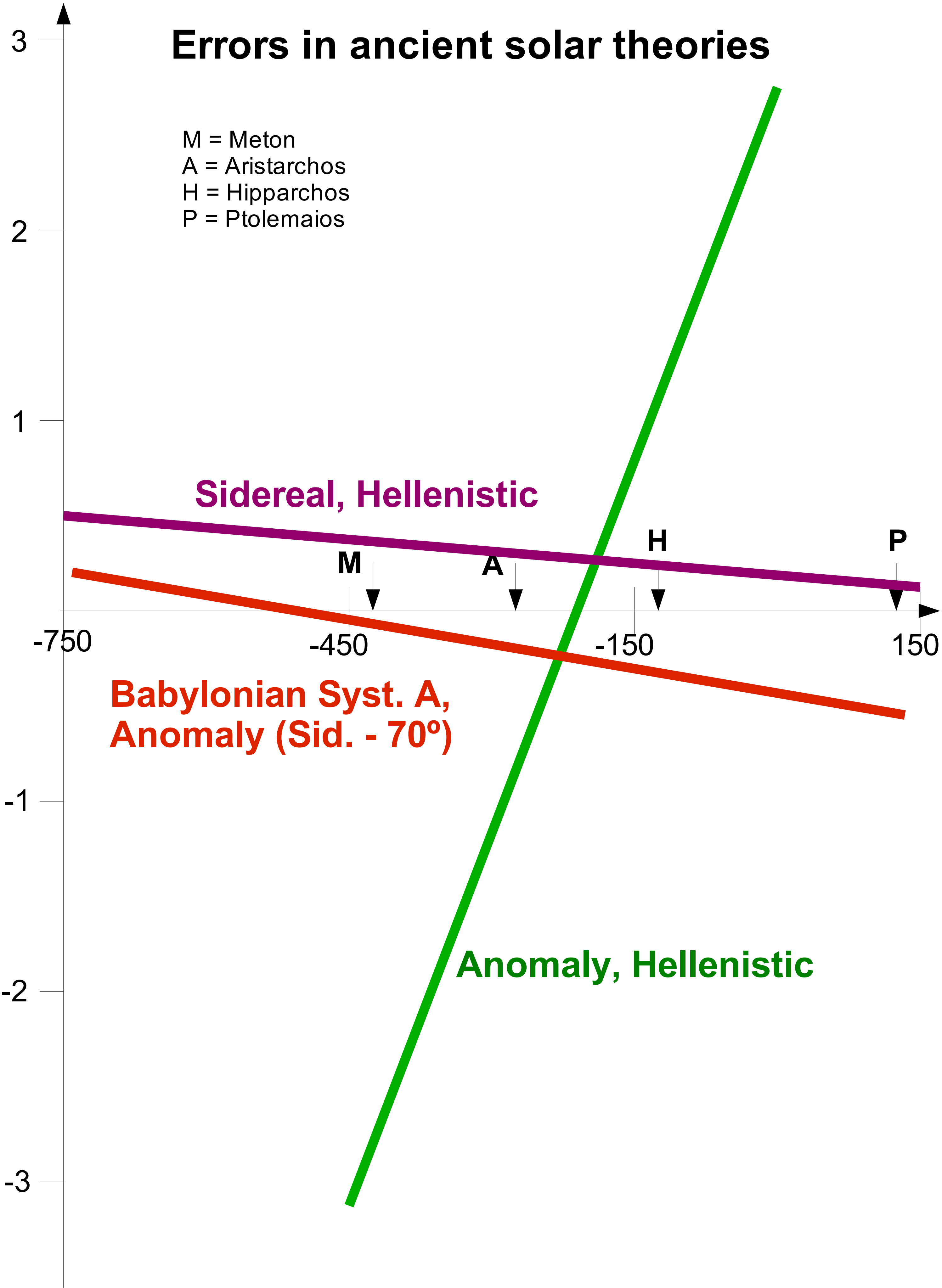


Figure 3: Possible connection between the positions of the earliest *Almagest* lunar eclipses and Spica on the one hand and the parameters of Babylonian solar System A and A' theories on the other. Babylonian longitude of velocity change, 163°, diminished by
93° produces the solar apogee used by the Greeks.

Errors in ancient solar theories



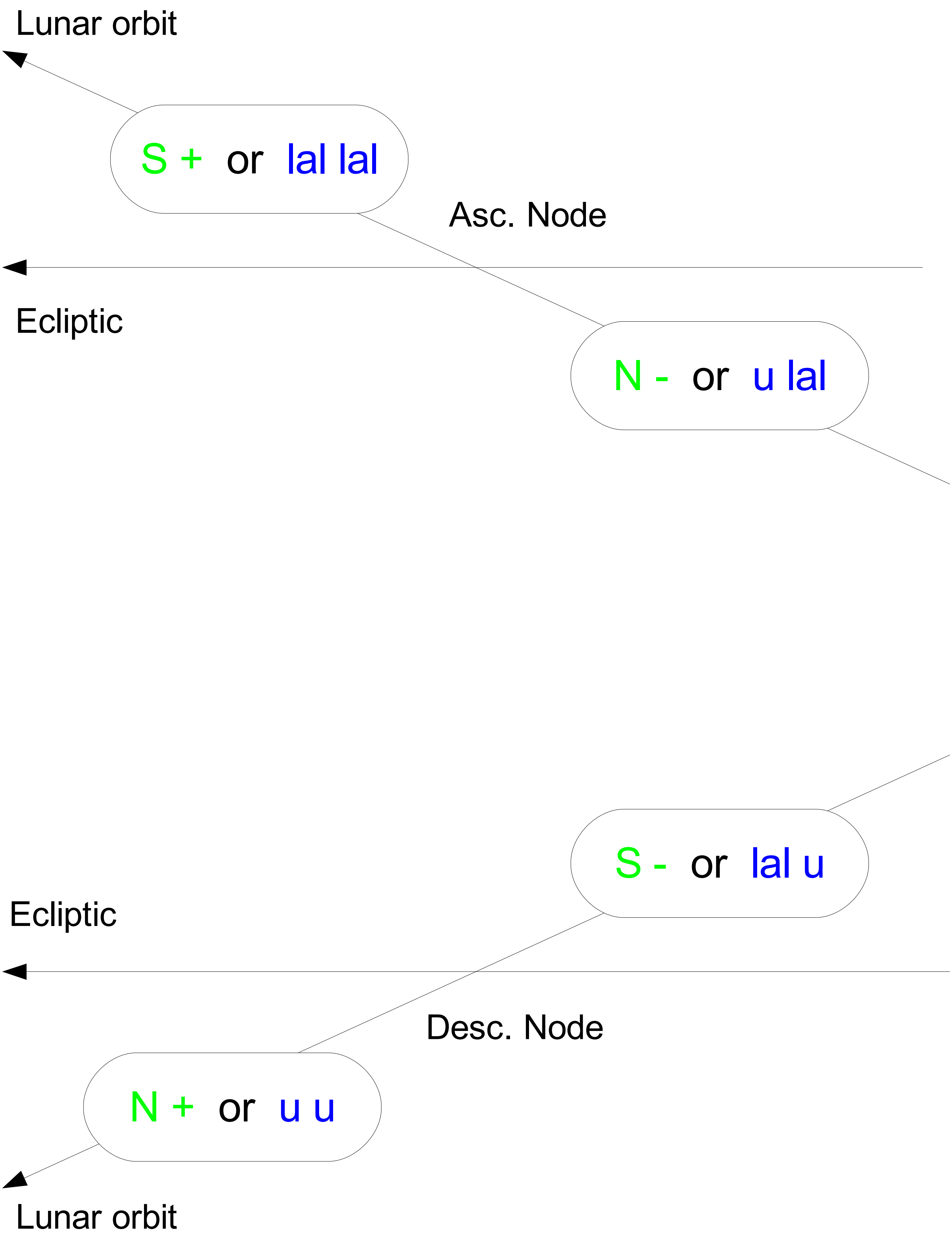


Figure 5: Fourfold classification of lunar eclipses

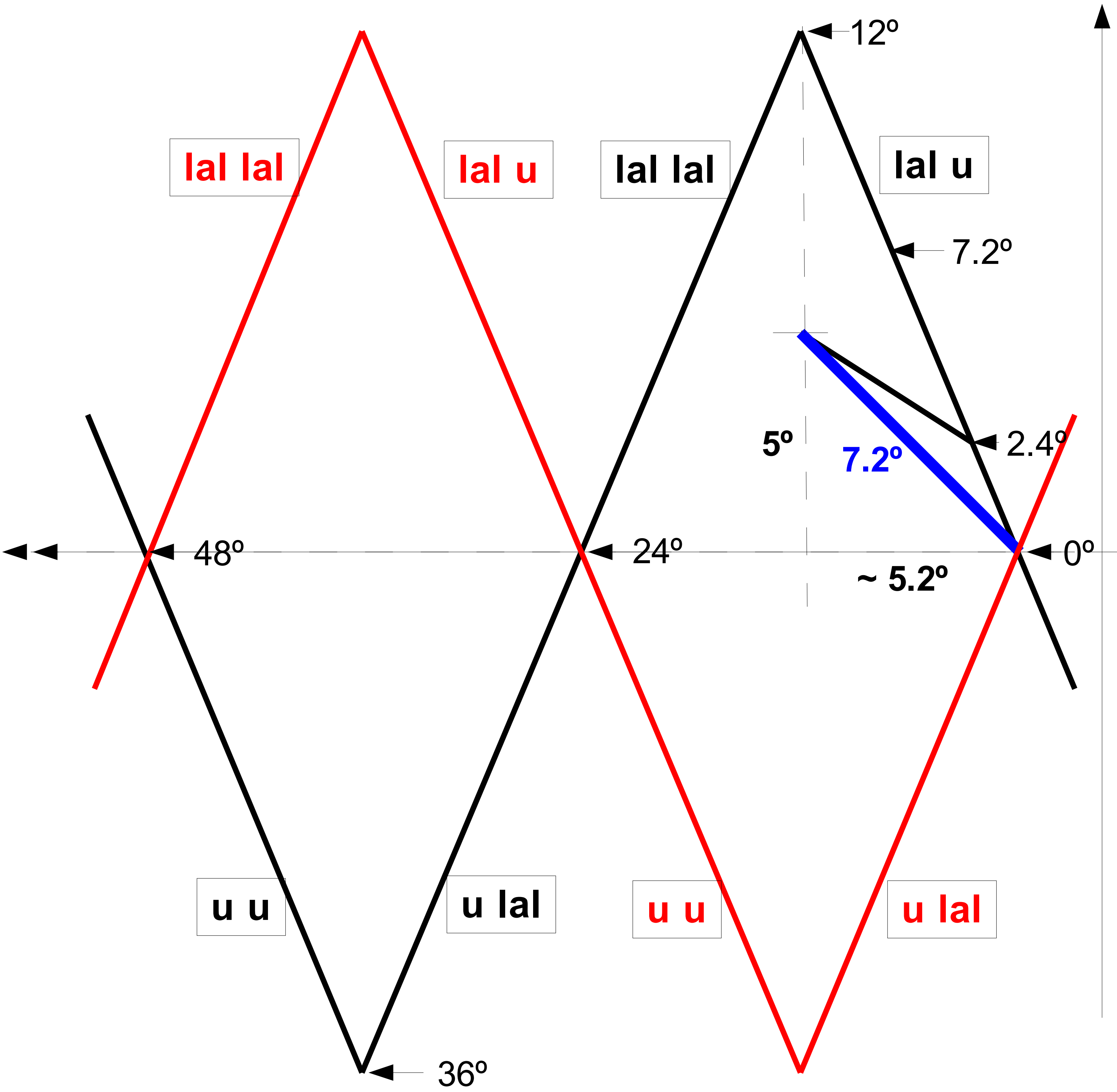


Figure 6: Constructon of Col. E in Babylonian system A eclipse theory. For details see text.

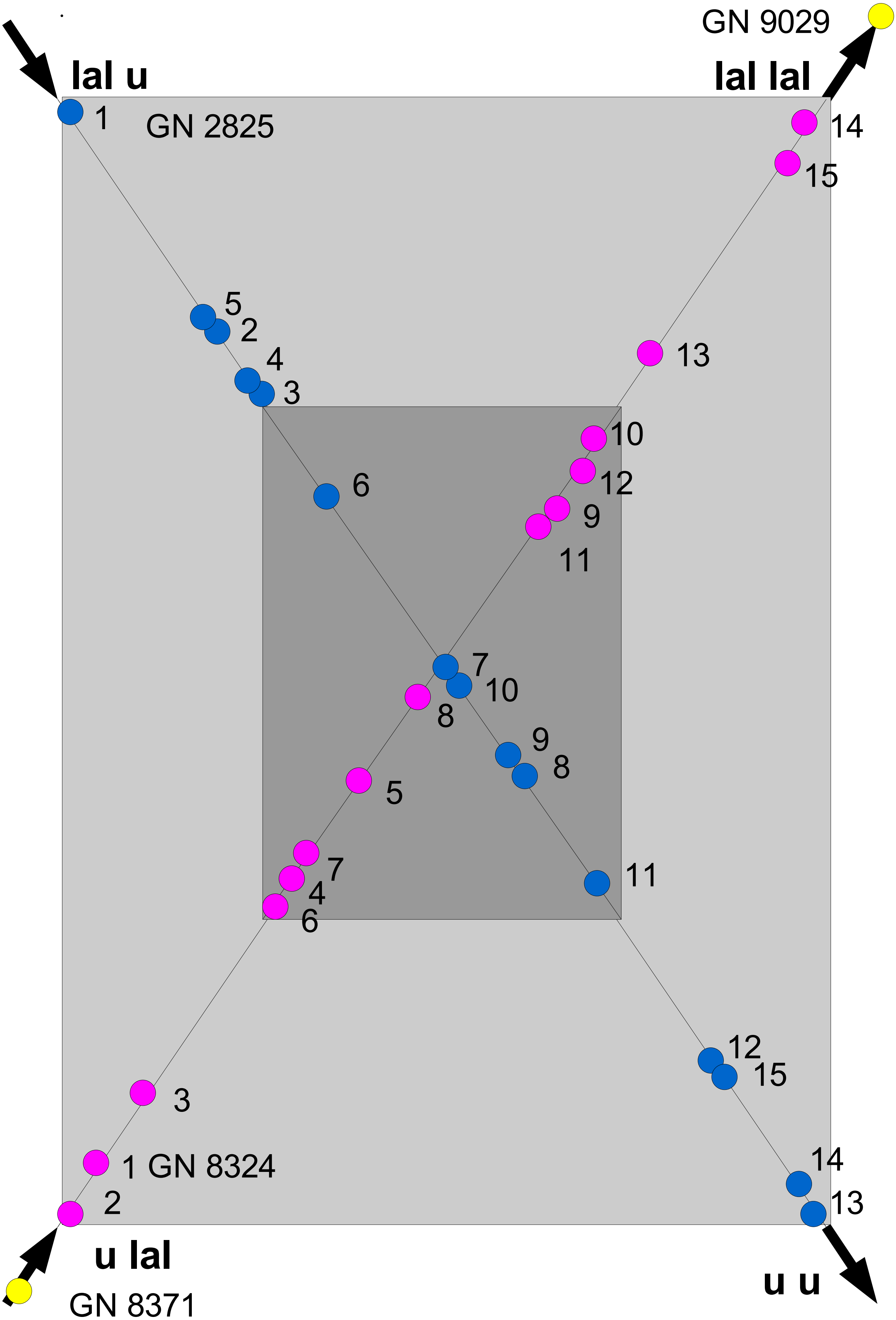
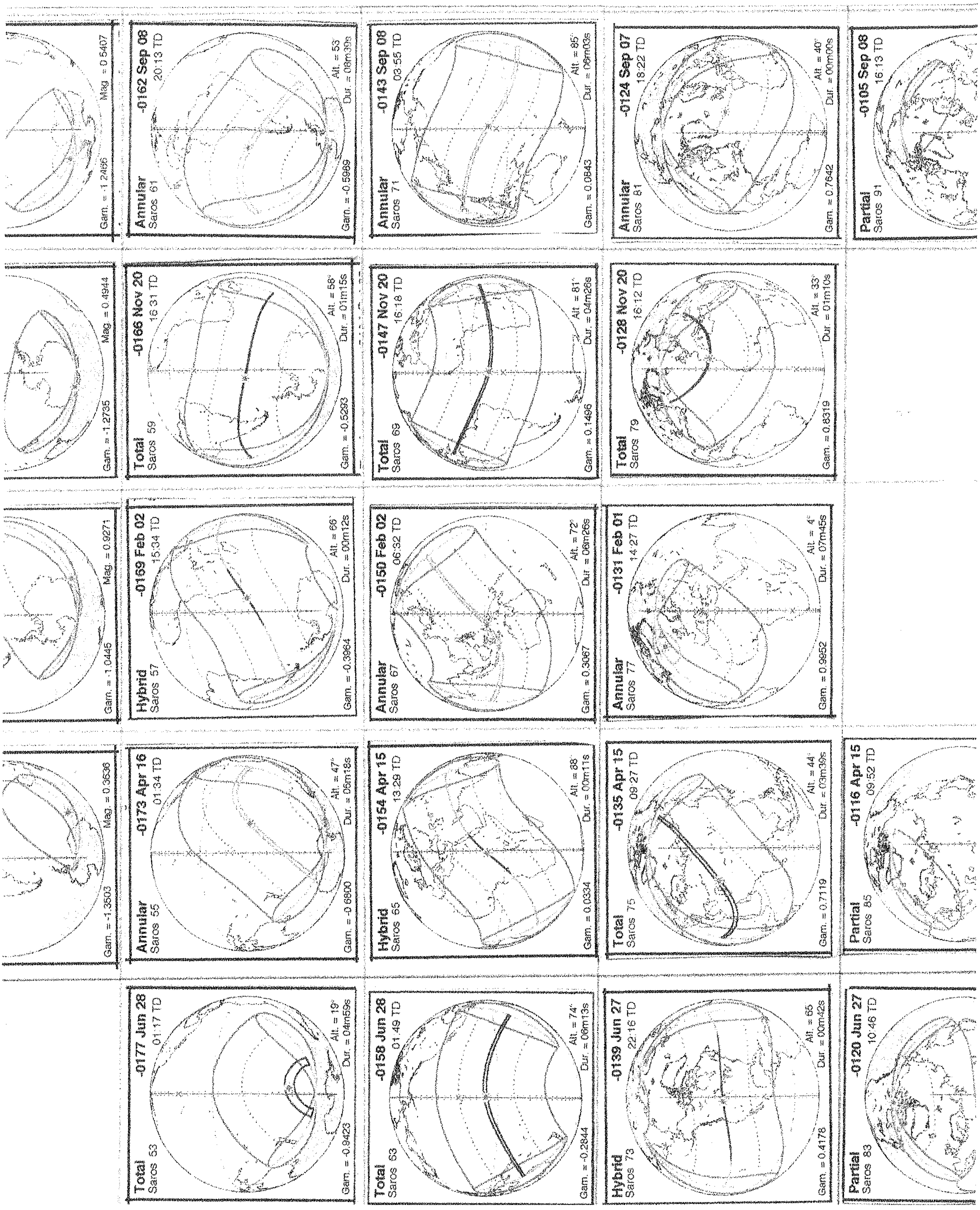


Figure. 7: Eclipse magnitudes from GN2825 through GN3483
and again from GN8324 through GN9076.

Modern sketches (Espenak & Meeus: 2006) of solar eclipse string members from the 2nd century BC



Time GN//YearMM	Place Knot//Col. B	Magnitude Col. E		NASA	Dev.	Av. Dev. (Rem)
2825//-772JN	26//275;07,30	lal u	0,4	1,3 S	0.9	
2872//-768AP	19//205;30	lal u	7,9	9,1	1,2	
2919//-764JA	12//133;08	lal u	10,2	11,7	1,5	
2966//-761NO	05//058;52	lal u	9	11,6	2,6	
3013//-757SE	33//344;36	lal u	7,6	8,8	1,2	
3060//-753JN	26//274;52,30	lal u	14,9	15,7 S	0,8	
3107//-749AP	19//205;15	u u	21,5	21 N	0,5	
3154//-745JA	12//132;52	u u	19,3	16,9	2,4	1,8 +/- 1,0
3201//-742NO	05//058;36	u u	20,6	17,7	2,9	
3248//-738SE	33//344;20	u u	21,9	20,3	1,6	
3295//-734JN	26//274;37,30	u u	14,5	13,2	1,3	
3342//-730AP	19//205	u u	7	5,9	1,1	
3389//-726JA	12//132;36	u u	4,8	2,5	2,3	
3436//-723NO	05//058;20	u u	6,1	1,6	4,5	
3483//-719SE	33//344;04	u u	7,4	5,9 N	1,5	(*Alm.* 3)
8324//-327JA	11//127	u lal	0,5	2	1,5	
8371//-324NO	04//052;44	u lal	-0,8	-3,2 N	-2,4	
8418//-320AU	32//338;45	u lal	-1,6	0,2	1,8	
8465//-316JN	25//269;07,30	u lal	6,1	4,3	-1,8	
8512//-312AP	18//199;30	u lal	13,8	13	-0,8	
8559//-308JA	11//126;44	u lal	15,4	17	1,6	
8606//-305NO	04//052;28	u lal	14,0	12,3	-1,7	
8653//-301SE	32//338;30	u lal	13,2	14,3	1,1	
8700//-297JN	25//268;52,30	u lal	20,9	20,2 N	-0,7	0,3 +/- 1,8
8747//-293AP	18//199;15	lal lal	17,5	15,9 S	1,6	
8794//-289JA	11//126;28	lal lal	14,7	12,9	1,8	
8841//-286NO	04//052;12	lal lal	16,0	16,2	-0,2	
8888//-282AU	32//338;15	lal lal	16,8	14,3	2,5	
8935//-278JN	25//268;37,30	lal lal	9,1	10,4	-1,3	
8982//-274AP	18//199	lal lal	1,4	1,5	-0,1	
9029//-270JA	11//126;12	lal lal	-0,1	-3,8 S	3,7	
9076//-267NO	04//051;56	lal lal	1,2	2,1	-0,9	
13917//125AP	17//193;45	lal u	4,7	1,7 S	-3	(*Alm.* 54)
13964//129JA	10//120:36	lal u	5,5	4	-1,5	
14011//132NO	03//046;20	lal u	4,2	3,9	-0,3	
14058//136AU	31//332;45	lal u	4,1	0,8	-3,3	
14105//140JN	24//263;07,30	lal u	11,8	9,5	-2,3	
14152//144AP	17//193;30	lal u	19,5	17,6	-1,9	
14199//148JA	10//120:20	lal u	20,3	18,7	-1,6	
14246//151NO	03//046;04	lal u	19,0	18,1	-0,9	-1,5 +/- 1,1
14293//155AU	31//332;30	lal u	19,0	17,3 S	-1,7	
14340//159JN	24//262;52,30	u u	18,2	19,5 N	-1,3	
14387//163AP	17//193;15	u u	10,5	12,9	-2,4	
14434//167JA	10//120:04	u u	9,7	10	-0,3	
14481//170NO	03//045;48	u u	11,1	10,2	0,9	
14528//174AU	31//332;15	u u	11,0	12,8	-1,6	
14575//178JN	24//262;37,30	u u	3,3	4,8 N	-1,5	

Eclipse strings for GN = p•47+5 around 750 B.C. from GN 2825 through 3483, again around A.D. 150 from from GN 13917 through 14575, and finally in between around 300 B.C. from GN 8371 (or 8324) through 9029 (or 9076). Note that (13917+3483)/2 = 8700, and 13917-3483 = (2•118 – 14)•

Time GN//YearMM	Place Knot//Col. B	Magnitude Col. E		NASA	Dev.	Av. Dev. (Rem.)
2960//-761MY	23//245;22,30	u lal	3,4	2,1 N	-1,3	
3007//-757MR	16//175;40	u lal	10,8	12	1,2	
3054//-754DE	09//101;24	u lal	9,5	11,4	1,9	
3101//-750OC	02//027;08	u lal	8,2	8,5	0,3	
3148//-746AU	30//314;45	u lal	10,4	12,3	1,9	
3195//-742MY	23//245;07,30	u lal	17,9	18 N	0,1	
3242//-738MR	16//175;24	lal lal	18,7	17,1 S	1,6	
3289//-735DE	09//101;08	lal lal	20	18,1	1,9	0,8 +/- 1,3
3336//-731OC	02//026;52	lal lal	21,4	20,2	1,2	
3383//-727AU	30//314;30	lal lal	19,1	17,6	1,5	
3430//-723MY	23//244;52,30	lal lal	11,4	11,4	0	
3477//-719MR	16//175;08	lal lal	1,3	1,6	-0,3	(*Alm.* 2)
3524//-716DE	09//100;52	lal lal	3,4	3,8	-0,4	
3571//-712OC	02//026;36	lal lal	5,6	6	-0,4	
3618//-708AU	30//314;15	lal lal	4,5	1,1 S	3,5	
8459//-317DE	08//095;16	lal u	-0,2	1,5	1,7	
8506//-313OC	01//021	lal u	-1,6	-1,8 S	-0,2	
8553//-309AU	29//309	lal u	1,5	-1,2	-2,7	
8600//-305MY	22//239;22,30	lal u	9,2	9,5	0,3	
8647//-301MR	15//169;16	lal u	15,9	13,9	-2	
8694//-298DE	08//095	lal u	14,6	15,8	1,2	
8741//-294OC	01//020;44	lal u	13,2	13,7	0,5	
8788//-290JL	29//308;45	lal u	16,3	13,9 S	-2,4	
8835//-286MY	22//239;0730	u u	20,8	20,5 N	0,3	0,2 +/- 1,7
8882//-282MR	15//169	u u	14,1	15,1	-1	
8929//-279DE	08//094;44	u u	15,5	12,7	2,8	
8976//-275OC	01//020;28	u u	16,8	16,5	0,3	
9023//-271JL	29//308;30	u u	16,7	14,8	1,9	
9070//-267MY	22//238;52,30	u u	6,0	4,2	1,8	
9117//-263MR	15//168;44	u u	-0,7	1	-1,7	
9164//-260DE	08//094;28	u u	0,6	-1,6	2,2	
9211//-256OC	01//020;12	u u	2,0	0,2 N	1,8	
9258//-252JL	29//308;15	u u	-1,2	0,7	-1,9	
14052//136MR	14//163;08	u lal	6,1	5,2 N	-0,9	(*Alm.* 73)
14099//139DE	07//088;52	u lal	4,7	2,6	-2,1	
14146//143OC	00//014;36	u lal	3,4	0,9	-2,5	
14193//147JL	28//303	u lal	7,2	5,9	-1,3	
14240//151MY	21//233;22,30	u lal	14,9	11	-3,9	
14287//155MR	14//162;52	u lal	20,9	19,7	-1,2	
14334//158DE	07//088;36	u lal	19,5	18,7	-0,8	
14381//162OC	00//014;20	u lal	18,2	15,4	-2,8	-1,7 +/- 1,1
14428//166JL	28//302;45	u lal	22,1	20,3 N	-1,8	
14475//170MY	21//233;07,30	lal lal	15,1	17,6 S	-2,5	
14522//174MR	14//162;36	lal lal	9,1	8,7	0,4	
14569//177DE	07//088;20	lal lal	10,5	11,5	-1	
14616//181OC	00//014;04	lal lal	11,8	13,3	-1,5	
14663//185JL	28//302;30	lal lal	7,9	8,5	-0,6	
14710//189MY	21//232;52,30	lal lal	0,2	3,4 S	-3,2	

Eclipse strings for GN = p•47+46 around 750 B.C. from GN 2960 through 3618, again around A.D. 150 from GN 14052 through 14710, and finally in between around 300 B.C. From GN 8506 (or 8459) through GN 9211 (or 9258). Note that (3477+14052+3•47)/2 = 8835, and (14052-3477) = (2•118-11)•47

Time GN//YearMM	**Place** Knot//col.B	**Magnitude** Col. E	NASA	**Dev.**	**Av. Dev.** (Rem.)
4703//-620AP	20//216;22,30	lal u 3,5	1,8 S	-1,7	*(Alm. 4)*
4750//-616FE	13//145;16	lal u 7,3	9,7	2,4	
4797//-613NO	06//071	lal u 6,0	7	1	
4844//-609SE	34//356;44	lal u 4,6	4,5	-0,1	
4891//-605JL	27//286;15	lal u 10,6	11,4	0,8	
4938//-601AP	20//216;37,30	lal u 18,3	17,7 S	-0,6	
4985//-597FE	13//145;16	lal u 22,1	19,4 N	3,3	
5032//-594NO	06//070;44	lal u 20,8	22,4	1,6	1,1+/-1,5
5079//-590SE	34//356;28	lal u 19,4	19,4 S	0	
5126//-586JL	27//286	u u 19,4	18,5 N	0,9	
5173//-582AP	20//216;22,30	u u 11,7	11,6	0,1	
5220//-578FE	13//144;44	u u 7,9	3,8	4,1	
5267//-575NO	06//070;28	u u 9,3	7,7	1,6	
5314//-571SE	34//356;12	u u 10,6	9,4	1,2	
5361//-567JL	27//285;45	u u 4,5	2,1 N	2,4	
10296//-168JL	26//280;30	u lal 1,5	-1.9 N	-3,4	
10343//-164AP	19//210;52,30	u lal 9,2	9,3	0,1	
10390//-160FE	12//138;52	u lal 12,3	11,1	-1,2	
10437//-157NO	05//064;36	u lal 10,9	10,6	-0,3	
10484//-153SE	33//350;20	u lal 9,6	10,5	0,9	
10531//-149JL	26//280;15	u lal 16,4	13,2 N	-3,2	
10578//-145AP	19//210;37,30	lal lal 20,8	20,7 S	*0,1*	*(Alm. 39)*
10625//-141FE	12//138;36	lal lal 17,8	17,8	0	-0,2+/-1,6
10672//-138NO	05//064;20	lal lal 19,1	18	1,1	
10719//-134SE	33//350;04	lal lal 20,5	19,9	0,6	
10766//-130JL	26//280	lal lal 13,6	15,5	-1,9	
10813//-126AP	19//210;22,30	lal lal 5,9	4,4	1,5	
10860//-122FE	12//138;20	lal lal 2,9	3,5	-0,6	
10907//-119NO	05//064;04	lal lal 4,3	3,6	0,7	
10954//-115SE	33//349;48	lal lal 5,6	3,6 S	2	

Eclipse strings for GN = p•47+3 around 600 B.C from GN 4703 through 5361,and again around 150 B.C. from GN 10296 through 10954 (or 11001). Note that 10578 – 4703 = (119+6)•47.

Time GN//YearMM	**Place** Knot//col. B	**Magnitude** Col. E	NASA	**Dev.**	**Av. Dev.** (Rem.)
36195//1926JN	20//239;37,30	lal u 5,1	-3,5 S	-8,6	
36242//1930AP	13//169;32	lal u 11,9	1,3	-10,6	
36289//1934JA	06//95;16	lal u 10,6	1,3	-9,3	
36336//1937NO	34//21;00	lal u 9,2	1,7	-7,5	
36383//1941SE	27//309;00	lal u 12,3	0,6	-11,7	
36430//1945JN	20//239;22,30	lal u 20,0	10,3 S	-9,7	
36477//1949AP	13//169;16	u u 18,1	17,1 S	-12,8	
36524//1949AP	06//95;00	u u 19,5	16	-9,3	
36571//1953JA	34//20;44	u u 20,8	15,8	-8,2	-9,4 +/- 1,5
36618//1960SE	27//308;45	u u 17,7	17,1 S	-10	
36665//1964JN	20//239;07,30	u u 10,0	18,7 N	-8,7	
36712//1968AP	13//169;00	u u 3,3	13,3	-10	
36759//1972JA	06//94;44	u u 4,6	12,6	-8	
36806//1975NO	34//20;28	u u 6,0	12,8	-6,8	
36853//1979SE	27//308;30	u u 2,9	13,1	-10,2	
36900//1983JN	20//238;52,30	u u -4,8	4,0 N	-8,8	

20th century eclipse string for GN = p•47+5 from GN 36195 through 36900 producing a long range check on ancient Babylonian column E.

RePoSS issues

#1 (2008-7) **Marco N. Pedersen**: "Wasan: Die japanische Mathematik der Tokugawa Ära (1600-1868)" (Masters thesis)

#2 (2004-8) **Simon Olling Rebsdorf**: "The Father, the Son, and the Stars: Bengt Strömgren and the History of Danish Twentieth Century Astronomy" (PhD dissertation)

#3 (2009-9) **Henrik Kragh Sørensen**: "For hele Norges skyld: Et causeri om Abel og Darwin" (Talk)

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