Astron. Astrophys. 205, L8–L10 (1988)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

ELP 2000-85 and the Dynamical Time – Universal Time relation

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Received June 21, accepted July 14, 1988

Summary. The new ephemeris of the Moon, ELP 2000-85, has been used to analyse some of more reliably documented historical eclipses of the Sun. The conclusion is that the presently available expressions of the Dynamical Time - Universal Time (DT - UT) difference are clearly inadequate for the use with this ephemeris for historical studies. The basic reason lies in the difference between mean lunar longitude in the new and older theories of the motion of the Moon. A provisional relation between the two times applicable presumably before about AD 1700 (back to about 2000 BC) reads in seconds of time

$$DT - UT = 35.0\ (t + 3.75)^2 + 40,$$

where t is time in Julian centuries elapsed from the epoch 2000.0. This equation includes a magnitude of the secular deceleration of the Earth rotation of 70 s/cy^2 or, in other units, 22 10^{-9} /cy.

Key words: Ephemerides - eclipses - Earth:rotation - time

With the appearance of the new theory of the motion of the Moon worked out in the Bureau des Longitudes (Chapront-Touzè and Chapront, 1983) recently emerged relatively simple, yet very accurate, semianalytical ephemeris of this body named ELP 2000-85 (Chapront-Touzè and Chapront, 1987, 1988), which seems very suitable for studies of historical observations of occultations and solar and lunar eclipses. Over a few thousands of years (since -1500) its internal accuracy is 10" or better, as compared to the JPL numerical integration LE51. Since the authors offer a ready FORTRAN coding of the ELP 2000-85 it may be expected that in the near future this ephemeris will become a sort of standard tool in analyses of ancient astronomical observations. Some of such analyses require the knowledge of the difference between the Dynamical Time (DT), which is the argument of the discussed ephemeris and is a direct extention of the Ephemeris Time (these two times can be considered equivalent for our purposes), and the Universal Time (UT).

The authors of ELP 2000-85 on passing suggested (in Chapront-Touzè and Chapront, 1988) to use the relation DT - UT derived by Morrison and Stephenson (1982), which is based on Babylonian observations of the eclipses of the Moon. I have used this relation in another study (Borkowski, 1988) and I found it to be indeed very acceptable, at least when the solar eclipses are concerned and older theories of the motion of the Moon used. However, in conjunction with the French ephemeris (ELP 2000-85) the suggested relation fails to give satisfactory predictions of ancient solar eclipses (and presumably also other astonomical phenomena, which I did not analyse). In fact, it should not be surprising because this ephemeris uses considerably different expression for the mean lunar longitude than does e.g. the Improved Lunar Ephemeris. In particular, it incorporates the secular tidal acceleration of the Moon of -23.895 $''/cy^2$, while more commonly used value reads -26 $''/cy^2$.

To estimate the quantity ΔT = DT - UT I have used the solar eclipses recorded in historical times between -2136 and 1715 of the common era, most of which were presented by Stephenson and Clark (1978). Firstly, I analysed in detail each eclipse with the aim to estimate a range of ΔT values that satisfy the stated condition of centrality. In two cases, concerning partial eclipses of 928 at Baghdad and -321 at Babylon, angular (altitude of the Sun) or timing information (duration of eclipse that occurred at sunset) from ancient records were used as landmarks for ΔT estimates. For this purpose I made use of the computer program described in Borkowski (1988) with original less accurate ephemerides replaced by ELP 2000-85 (a FORTRAN programmed version supplied by its authors which I slightly modified to fit my philosophy and to include the nutation theory) and the Stumpff's algorithm for the motion of the Earth (Stumpff, 1979, 1980; also this algorithm I extended by adding the nutation to get the apparent coordinates of the Sun). Then a least squares fit of the estimated ΔT values to the quadratic polynomial in time was performed. The usual method of fit I modified so as to carry minimization of the summed squares of deviations above or below the mentioned range of acceptable ΔT values, rather than deviations from certain point inside the

Table 1. Eclipses of the Sun used for derivation of DT – UT difference. The 'fit' denotes values obtained from Eq. (1) and 'res.' stands for the deviation outside the 'min.' (usually the second contact) to 'max.' (usually the third contact) range. The 'computed' data correspond to the 'fit' values of DT – UT. The 'observed' phases of 1 or >1 refer to a totality, while these of the form >0.9... to an annular eclipse

Date Year	M	D	Place	DT – UT [s] min.	max.	fit	res.	Eclipse phase observed	computed
1715	05	03	England*	-23	-11	69	-80	1	0.997/1.003
1567	04	09	Roma	86	158	52	34	1	0.998
1560	08	21	Coimbra	-523	179	55	0	>1	1.008
1485	03	16	Melk	-4540	2040	108	0	>1	1.020
1415	06	07	Prague	-1500	628	194	0	>1	1.016
1406	06	16	Braunschweig	-198	1400	207	0	>1	1.014
1267	05	25	Constantinopole	-810	736	488	0	>1	1.003
1241	10	06	Stade/Cairo(?)	521	1007	554	0	>1	1.000/1.017
1239	06	03	Southern Europe	718	1200	560	158	>1	0.993-1.036
1221	05	23	Kerulen River	<-5400	1043	610	0	>1	1.011
1176	04	11	Antioch	-348	1482	745	0	>1	1.022
1124	08	11	Novgorod	837	2571	916	0	>1	1.002
1133	08	02	Salzburg	146	1334	885	0	>1	1.025
975	08	10	Kyoto	954	4295	1516	0	>1	1.007
968	12	22	Constantinopole	1411	4680	1546	0	>1	1.001
928	08	18	Baghdad**	1357	1615	1737	-122		0.218
912	06	17	Cordoba(?)	1007	2453	1817	0	>1	1.022
840	05	05	Bergamo	<-3780	6238	2195	0	>1	1.012
522	06	10	Nan-ching(?)	3046	4678	4295	0	>1	1.018
516	04	18	Nan-ching(?)	3146	4730	4343	0	>0.939	0.953
120	01	18	Lo-yang	7604	8474	7967	0	>1	1.014
65	12	16	Kuang-ling	8334	8838	8547	0	>1	1.010
-135	04	15	Babylon***	10336	11272	10878	0	>1	1.021
-180	03	04	Ch'ang-an	10990	11932	11441	0	>1	1.020
-197	08	07	Ch'ang-an	5650	11716	11651	0	>0.950	0.951
-321	09	26	Babylon	13200	13322	13285	0		0.087
-548	06	19	Chu-fu	15751	19789	16560	0	>1	1.010
-600	09	20	Ying(?)	17323	18105	17357	0	>1	1.001
-708	07	17	Chu-fu	19091	20045	19082	9	>1	0.999
-1374	05	03	Ugarit	30638	31760	31512	0	>1	1.004
-2136	10	22	An-yi****	49261	50216	49528	0	>0.967	0.976

Notes to Table 1:
* – at Darrington and Lewes (the path of totality limits); ref.: Morrison et al. (1988)
** – DT – UT estimated from observed altitude of the Sun of about 12 (+/-0.5) deg; computed value is 11.0 deg.
*** – DT – UT estimated from observed duration of this eclipse of about 12 (+/-1) min. (till sunset); computed value is 12.5 min.
**** – Ref.: Wang and Siscoe (1980) and P.K. Wang (1988, private communication); assumed geographical coordinates were 35.1 (latitude) and 111.2 deg (longitude)
? – uncertain location

range. This procedure effectively eliminates observations that are not critical for the determination of ΔT curve.

As a result of the above described fit the following expression for DT (in seconds) has been established:

$$DT - UT = 35.0\ (t + 3.75)^2 + 40, \qquad (1)$$

where t is time measured in Julian centuries since 2000.0. Table 1 and Fig. 1 contain details of the analysed data and final residuals. Eq. (1) differs from that of Morrison and Stephenson (1982) by varying amount and up to about 25 minutes of time in the considered historical period (the maximum is reached near 700 BC). Though, due to limited observational material, I am not in position to claim this equation to be definite, I believe it is good to a few minutes over the entire period and thus may prove useful for researchers who need such relation immediately.

The numerical coefficient of 35.0 s/cy^2 in the formula for ΔT is interpreted as one half of the secular deceleration of the Earth rotation. It will be noted that our value of 70 s/cy^2 or, in relative angular units, 22 $\cdot 10^{-9}$/cy does not differ much from other authors' determinations which range from about 60 to more than 90 s/cy^2. In fact, it is enveloped by two recent results of 65 and 72.82 s/cy^2 (Morrison and Stephenson, 1982, and Li Zhisen and Yang Xihong, 1985). It is difficult to assess accuracy to our result but the two following observations may be of some use. If the first eclipse listed in Table 1 is omitted in the analysis then the deceleration rises to 72.8 s/cy^2. Judging by the formal standard deviations of the modified least

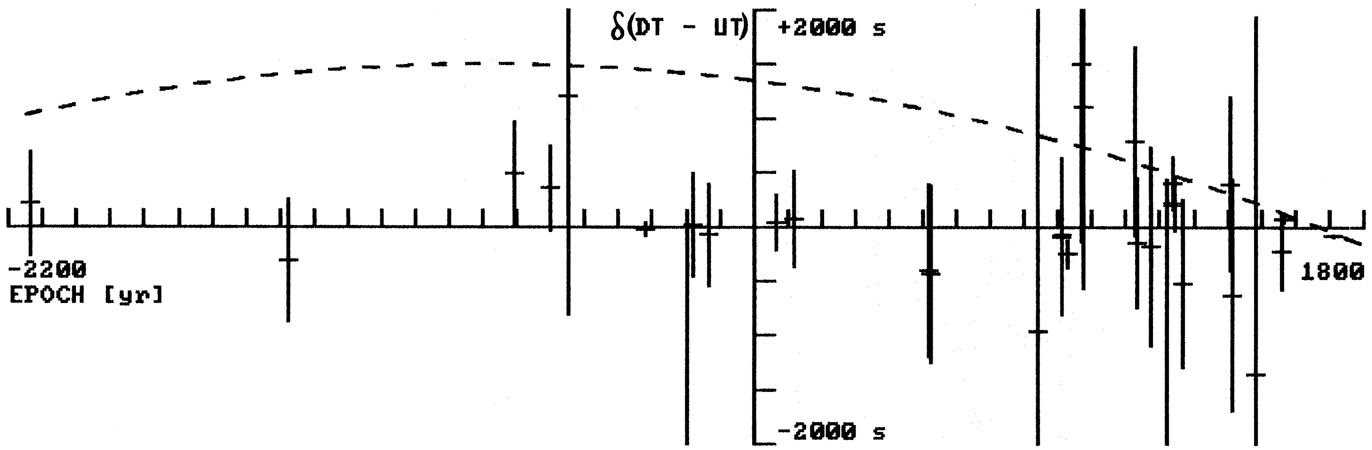

Fig.1. Plot of allowed ranges of the DT - UT differences for eclipses of Table 1 relative to the mean ΔT curve [Eq. (1)] represented here by the abscissa axis. The abscissa axis is scaled every 100 years from -2200 to 1800, and the ordinate axis is marked every 500 s between the range of +/-2000 s. Each vertical bar is halved by a short horizontal bar to mark the centre of the allowed range. The broken curve shows the ΔT of Morrison and Stephenson (1982)

squares fit alone one arrives at the uncertainty of about 1.4 s/cy^2, which certainly is still too optimistic in view of the assumed modified definition of residua. In any case, the near future requires further work to be done encompassing also other historical eclipses (solar and lunar) and occultations of stars.

L.V. Morrison (1988, private communication) criticised my use of rather unreliable ancient (6th century and earlier) records of total solar eclipses. The reader will observe, however, that of them only the eclipse of -708 (Chu-fu) contributed to the solution described by Eq. (1), the remaining 12 eclipses happened not to be critical.

The ephemeris ELP 2000-85 can be modified to account for other adopted values of the lunar tidal acceleration. For comparison purposes I have used the lunar arguments listed in Table 8 (plus adequately changed expression for their L) of Chapront-Touzé and Chapront (1988) as the replacement of those originally included in the FORTRAN code of the ephemeris. The modification incorporates the tidal acceleration of -26.305 "/cy^2 and makes the ephemeris to closely agree with the LE51. Then, I have computed the circumstances of all the eclipses listed in Table 1 using different expressions for the ΔT. The expression of Morrison and Stephenson (1982) gave satisfactory predictions only back to 912 (excluding the Baghdad eclipse). Similarly, unsuitable with the modified lunar ephemeris appears Eq. (1) above. In contrast, a 'two-acceleration' model of Stephenson and Morrison (1984) performed much better in this respect. It only failed to predict the 'observed' (Table 1) phases at Kuang-ling, Ugarit and An-yi, which are considered to be less reliable.

Acknowledgements. I would like to thank the authors of the ELP 2000-85 for a copy of their program and associated printed materials, which made this work possible. I am also grateful to Dr Dr L.V. Morrison and M. Chapront-Touzé for helpful criticisms of, and comments on an earlier version of this letter. Prof. S. Gorgolewski kindly corrected my English.

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