ASTRONOMICAL FINE-TUNING OF THE CHRONOLOGY OF THE HAMMURABI AGE*

Teije de Jong**

1. Introduction

"Mesopotamian chronology is conventionally based on texts: king lists, eponym lists, dated documents, synchronisms, royal inscriptions, etc." (Hunger 2009). At present the relative chronologies of the Old Assyrian period and of the Hammurabi dynasty — together covering about three centuries — are fairly well established (Pruzsinszky 2009). Putting this relative chronological framework on an absolute footing has so far turned out to be quite difficult. Present proposals for the beginning of the reign of Hammurabi range from 1848 BC (Long Chronology, Huber *et al*. 1982) to 1696 BC (Ultra Short Chronology, Gasche et al. 1998), corresponding to an uncertainty margin of about 150 years. To avoid the confusion created by this uncertainty and in the absence of anything better the Assyriological community has adopted the so-called (High) Middle Chronology (Hammurabi 1 = 1792 BC) as a working hypothesis. The Middle Chronology has served as a general historical reference frame for the Old Babylonian period over the past half century.

The absolute dating of relative chronological sequences has traditionally been based on ancient records of astronomical observations like solar and lunar eclipses, observations of heliacal risings and settings of the planets and on calendar information. Until recently astronomical chronology was the only "hard" scientific method available to provide absolute calibrations of historical records. During the last decades dendrochronology and radiocarbon dating have become increasingly important as additional chronological tools for the Ancient Near East (e.g. Manning *et al*. 2001).

Recently Barjamovic, Hertel and Larsen (2012) in *Ups and Downs at Kanesh* have succeeded in reconstructing the Old Assyrian eponym list over a time span of 255 consecutive years. By connecting their revised eponym list (REL) to the radiocarbon dating of tree-ring

* This paper has its origin in a lecture that I presented at the workshop "Towards an absolute chronology of Mesopotamia during the second millennium BC". This workshop was organized by Klaas Veenhof and myself during the 58th Rencontre Assyriologique Internationale in Leiden, the Netherlands in July 2012. After the meeting and the ensuing discussion I realized that the revision of the list of Old Assyrian eponyms (presented by Gojko Barjamovic at the workshop) and the radiocarbon dating of tree ring sequences in beams used in the construction of the Waršama palace in Kanesh (presented by Sturt Manning) provided such severe constraints to the absolute calibration of the Old Assyrian chronology that the problem addressed in the workshop might be considered solved with an uncertainty margin of only ±10 years. I also realized that the Venus observations during the reign of the Old Babylonian king Ammī-ṣaduqa and the solar eclipse around the birth of the Old Assyrian king Šamši-Adad, which by themselves provided insufficient constraints to resolve the problem of the Old Babylonian chronology, could quite well be used to fine-tune the absolute chronology to the ultimate accuracy of 1 year.

** Astronomical Institute 'Anton Pannekoek', University of Amsterdam, P.O. Box 94249, 1090 GE Amsterdam, the Netherlands; t.dejong@uva.nl.

sequences in wooden beams (Newton and Kuniholm 2004; Manning *et al*. 2010) used in the building of the Waršama Palace in Kanesh (ancient Kültepe near Kayseri in Central Turkey) they were able to put the relative chronology of the REL on an absolute basis with an uncertainty of about ±10 years at the 95% confidence level. Among other things this chronological calibration constrains the death of Šamši-Adad to 1776 BC ± 10 yrs. Using the well-established synchronism that Šamši-Adad died in the 18th year of the reign of Hammurabi (Charpin and Ziegler 2003) this implies an absolute date for the first year of the latter's reign of 1793 BC ± 10 yrs, a date for the first year of the reign of king Ammī-ṣaduqa of 1647 BC ± 10 yrs, and a date for the fall of Babylon of 1596 BC ± 10 yrs. Barjamovic *et al*. note — somewhat to their surprise — that these dates almost exactly match the (High) Middle Chronology.

In this paper I will investigate whether astronomical data can be used for fine-tuning the chronology of the Hammurabi dynasty now that the uncertainty margin has been reduced to about 20 years. The available astronomical data consist of:

– a series of Venus observations during the reign of the Old Babylonian king Ammī-ṣaduqa recorded on tablet 63 of the omen series *Enūma Anu Enlil* (Reiner and Pingree 1975; Huber *et al*. 1982; Mebert 2010),
– months of 30-day length during the reigns of Ammī-ditāna and of Ammī-ṣaduqa as recorded in administrative and economic texts (Huber *et al*.1982; Mebert 2010),
– a solar eclipse around the birth of the Assyrian king Šamši-Adad (see Barjamovic *et al*. 2012, 32ff.), and
– a lunar eclipse reported by the diviner Asqūdum to the king of Mari (Banjevic 2006; Mebert 2010).

These data have been used in the past in inconclusive attempts to put the Old Babylonian chronology on an absolute footing. The most recent attempt is by Mebert (2010) who presents a useful review of previous work and suggests a new absolute Old Babylonian chronology where the reign of Hammurabi begins in 1720 BC. His proposal is critically reviewed by Huber (2011) and de Jong (2013).

2. *The Venus observations of Ammī-ṣaduqa*

Almost exactly one hundred years ago the German Jesuit Franz Xaver Kugler[1] published his discovery that the year formula of year 8 of the Old Babylonian king Ammī-ṣaduqa appeared in a list of observations of the planet Venus in the omen series *Enūma Anu Enlil*. Ever since that time the Venus observations of Ammī-ṣaduqa have taken a central position in all attempts to put the Old Babylonian chronology on an absolute footing.

The omen series *Enūma Anu Enlil* consists of 70 tablets, copied and in use for celestial divination during two millennia of Mesopotamian cultural activity. Tablet 63 contains dates in the Babylonian lunar calendar of observations of Venus and associated omina. In omen no. 10 reference is made to "The year of the Golden Throne", known to be the 8th year of the reign of king Ammī-ṣaduqa, great-great grandson of the famous Babylonian king Hammurabi. Venus is named in the text as Nin-si$_4$-an-na, the name current in the late Sumerian period and in the time of the Old Babylonian dynasty (2000-1600 BC).

[1] F.X. Kugler, *Sternkunde und Sterndienst in Babel*, II. Buch, II. Teil, 1. Heft (1912), p. 257ff.

The most recent edition of Tablet 63 is based[2] on about twenty (fragments of) tablets that could be traced back to nine sources and three manuscript families. Due to the antiquity of the original observations and the many times the tablet must have been copied in the course of more than 1000 years the text may be corrupted, edited and added onto. The text contains in total sixty omina of which only a fraction may be associated with actual Venus observations. According to Reiner and Pingree the most reliable observations of Venus are the first 20 ones contained in the first 10 omina and covering the first 8 years of Ammī-ṣaduqa's reign (one 8-year Venus period). Huber *et al*. (1982) following van der Waerden (1945/8) argue that observations 21-40 associated with the next 10 omina (and the next 8-year Venus period) are indeed a continuation of the first 20 observations, but that in this set more observations are corrupted by scribal errors. The set of the most reliable observations contains omen no. 10 in which reference is made to the "Year of the Golden Throne" (Ammī-ṣaduqa year 8). As a professional astronomer there is no doubt in my mind that the majority of the data contained in the first 20 omina of the Venus tablet are based on genuine astronomical observations.

Over the past century there have been many attempts to astronomically date the reign of Ammī-ṣaduqa by selecting a "best data set" from the text and fitting that to computed Venus dates. The most authoritative study is that by Huber *et al*. (1982) who find that there are four possible Venus chronologies: Ammī-ṣaduqa 1 = 1702 BC ("Long Chronology"), 1646/1638 BC ("Middle Chronologies"), or 1582 BC ("Short Chronology"). Already more than 70 years ago Neugebauer (1941) had pointed out that the Venus observations — while providing a number of possible candidate chronologies — are by themselves not sufficiently discriminating to make a definitive choice. Other historical, archeological and/or astronomical constraints are required to choose between the different possible chronologies.

Huber *et al*. (1982) expressed preference for the Long Chronology (1702 BC) on the basis of a best fit to (independent) Old Babylonian month length data (see section 4). Using archeological evidence largely based on pottery sequences Gasche *et al*. (1998) have argued that the Old Babylonian chronology has to be shortened considerably compared to the traditional Middle Chronology. They proposed a date for Ammī-ṣaduqa year 1 of 1550 BC, implying a date of 1696 BC for the beginning of the reign of Hammurabi (New Chronology, also referred to as Ultra Short Chronology). This proposal has led to a lively debate in the literature (see Pruzsinszky 2009; Roaf 2012), but has not resulted in finally resolving the question. The fact that the Ultra Short Chronology is not supported by the Venus observations as pointed out by Huber (2000) has cast severe doubt on its credibility.

Based on the status of the atmosphere in Babylon that can be extracted from the Venus observations de Jong and Foertmeyer (2010) have suggested that three of the four observations in omina 14 and 15, previously discarded as corrupted by scribal errors, may be trustworthy after all if they are interpreted as showing traces of enhanced extinction in the atmosphere due to aerosols produced in the violent eruption of the volcano on the Greek island Thera (present-day Santorini)[3] that created havoc in the Eastern Mediterranean in the seventeenth century BC (e.g. Bruins *et al*. 2008). De Jong and Foertmeyer show that the radiocarbon dating of the remains of an olive branch that was buried by the eruption to 1613 BC +14/–13 yrs (at the 95% confidence level) by Friedrich *et al*. (2006) supports the Low Middle Chronology

[2] Reiner and Pingree (1975), p. 11-12.
[3] Peter Huber pointed out to me recently that this had been suggested earlier by J.D. Weir (1972, p. 30-31).

(Ammī-ṣaduqa 1 = 1638 BC) and that, if the Low Middle Chronology is adopted, the eruption can be more precisely dated to 1628/1627 BC.

3. Dating the Venus observations

Central in Babylonian astronomical practice is the recording of the dates of first appearance and disappearance of the planets. Because the inner planet Venus always stays within an angular distance of 48° from the Sun as seen from the Earth it experiences a repeating cycle of four consecutive appearances and disappearances: two as morning star (first appearance and disappearance in the East), and two as evening star (first appearance and disappearance in the West). Several passages in the Babylonian astronomical compendium *MUL.APIN*[4] show that already in the second millennium BC Babylonian astronomers were well aware of the intricacies of the motion of the planet Venus, its appearances and disappearances and its periods of invisibility. The Venus tablet of Ammī-ṣaduqa contains the earliest Babylonian collection of such observations.

It takes Venus 584 days to go through the cycle of two first appearances and two disappearances. After five cycles (10 first appearances and 10 disappearances) Venus reappears at approximately the same position in the sky (shifted backwards by about 2.5° in longitude). These 5 cycles correspond to a little less than eight years, the well-known Babylonian 8-year period of Venus (more precisely 99 lunar months – 4 days in the Babylonian lunar calendar, see Hunger and Pingree 1999, p. 203ff).

The minimum angular distance from the Sun for Venus to become visible near the horizon (the so-called *arcus visionis*) can be estimated from Neo-Babylonian observations of Venus during the last six centuries BC. This has most recently been done in two independent studies by Mebert (2010) and by de Jong (2012) with quite similar results, based on about 100 usable observational records from the *Astronomical Diaries*.[5]

Using his newly derived values of the *arcus visionis* Mebert (2010) has suggested that another chronology should be added to the list of candidate Venus chronologies, and that this chronology (Ammī-ṣaduqa 1 = 1574 BC) even provides the best fit to the Venus observations. While the 1574 BC chronology is a valid candidate there is no reason to prefer it above other candidate chronologies based on the Venus observations alone, as pointed out by Huber (2011) and de Jong (2013). This will be confirmed below from an analysis of all possible Venus chronologies where Ammī-ṣaduqa year 1 varies from 1710 to 1550 BC, the traditional uncertainty margin in the Old Babylonian chronology.

It is instructive to first consider one particular observation in some detail before studying a larger ensemble of Venus observations. In Table 1 I show in column (iii) the Julian dates of observation no. 2, the first appearance in the East (Morning First) of Venus on the 18th day of the month *Šabatu* (month XI) in year 1 of Ammī-ṣaduqa, for all possible Venus chronologies listed in columns (i) and (ii). Column (iv) shows the computed dates using an *arcus visionis* threshold value of 8.0° for Morning First observations of Venus taken from Table 2. In column (v) of Table 1 I list the computed Babylonian day no. and in column (vi) the difference in days

[4] Hunger and Pingree (1989), p.81-85.

[5] For the precise reference to volumes I-III of the *Astronomical Diaries and Related Texts from Babylonia* see the bibliography in de Jong (2012).

δd between the observed and computed dates. For details of the way in which these calculations are carried out the reader is referred to my earlier paper (de Jong 2012).

Notice that the values of δd in Table 1 change on average by –4 days from one to the next Venus chronology as expected on the basis of the 8-year (more precisely 99 lunar months –4 days) period of Venus. Notice also that the Julian dates in column (iv) recede on average by 2.5 days due to the fact that after 8 years Venus reappears at a position in the sky about 2.5° backwards in longitude which causes a slow drift backwards through the seasons in the course of time.

In order to keep the values of δd limited to at most half a lunar month the conversion of the observed date to Julian dates in column (iii) jumps twice (at the dashed lines) by one lunar month (accommodated into the Babylonian lunar calendar by intercalation). Since the Babylonian date of the Venus observation is 18 *Šabatu* (month XI) this implies that the first day (*Nisannu* 1) of year 2 of Ammī-ṣaduqa falls 42 days after the Venus observation; thus between 1 and 15 May for the first six chronologies in Table 1, between 13 and 30 April for the next eight chronologies and between 30 March and 12 April for the last seven chronologies in Table 1. We do not know how well the Old Babylonian calendar was lined up with the seasons and since large deviations (up to several months) are known to have occurred during the reigns of Hammurabi and Ammī-ṣaduqa[6] none of the chronologies in Table 1 can be confirmed or discarded on this basis.

According to the data in Table 1, based on Venus observation no. 2 alone one would select the 1694, 1638 and 1574 BC chronologies as the most probable candidate chronologies because the computed date coincides or differs by at most one day from the observed date. Notice that acceptable Venus candidate chronologies are separated by 56 or 64 years because to fit the observed date the computed Babylonian day has to shift by about one lunar month between two candidate chronologies corresponding to 7 or 8 eight-year periods.

In a similar way we now determine the best fitting Venus chronology by comparing the first 20 observations of the Venus text with astronomically predicted dates. According to Reiner and Pingree (1975) the first 20 observations, covering the first 8 years of the reign of Ammī-ṣaduqa, constitute the most reliable set. The results of this comparison are shown in Tables 3a and 3b where only those candidate chronologies are retained that have been proposed in the past or that otherwise provide a good fit to the observations.

The first columns in Tables 3a and 3b contain the observational parameters as given in the text according to Huber *et al*. (1982) for the first 19 observations (observation nr. 20 does not give a date but contains the reference to the "Year of the Golden Throne"). The Babylonian day numbers Bd' are the ones to be used for comparison with the computed dates for each chronology. For first appearances (MF and EF) the Bd' numbers are equal to the day numbers Bd in the text but for disappearances they have been decreased by one with respect to the text to convert to days of last appearance (ML and EL) which can be more directly compared to computed dates (see de Jong 2012). The predicted dates are computed using the *arcus visionis* values listed in column (ii) of Table 2. Values of δd are now given for each observation for the chronologies listed in Tables 3a and 3b. The mean value of δd and its standard deviation are given in the last two entries of the Tables for each chronology.

[6] Huber *et al*. (1982), p. 8.

The magnitude of the standard deviations in the last entry of Tables 3a and 3b is a measure of how well the pattern of first and last appearances of Venus is reproduced by the observed dates (should be minimal for the best fitting chronology). The magnitude of the mean of δd in the one-but-last entry of the Tables is a measure of how well the observed dates line up with the computed dates in the lunar calendar (should be smaller than the standard deviation for the best-fitting chronologies). Notice that the mean value of δd shifts by about –4 days between the two chronologies within each pair (1702/1694 BC, 1646/1638 BC and 1582/1574 BC), as expected on the basis of the 8-year period of Venus.

In computing the mean value of δd and its standard deviation in the last two entries of Tables 3a and 3b I have omitted observation no. 17 (δd-values in square brackets in Tables 3a and 3b) because it is out of range for all realistic candidate chronologies.[7] This observation was also excluded by Huber *et al*. (1982) and by Mebert (2010) who assumed that the text of this observation was corrupted. A few other observations, also excluded by Huber *et al*. (nos. 10 and 18) and by Mebert (no. 18), are retained here because they are within the expected range for at least one of the chronologies considered. It is important to realize that in spite of the fact that the quality of fit improves (smaller values of the standard deviation) when observations nos. 10 and 18 are also excluded from the averaging process, this has little effect on the relative ranking of the different candidate chronologies.[8]

Notice that on average the differences between observed and computed dates are significantly smaller for EL and MF observations than for ML and EF observations.[9] This was first noted by van der Waerden (1945/8) and is discussed in detail by de Jong (2012). It is due to differences in the relative motion of Venus with respect to the Sun near inner and outer conjunction. It also shows up in the analysis of the *arcus visionis* values derived from Neo- and Late Babylonian observation by de Jong (2012) as illustrated in columns (iii) to (v) of Table 2. From the observed standard deviations in the *arcus visionis* values shown in column (iii) of Table 2 it follows that 95% of all observed *arcus visionis* values are expected to fall within a range of ±2σ around the mean and combined with the change in the *arcus visionis* per day in column (iv), one then finds that for EL and MF observations 95% are expected to fall within a range of about ±3 days around the expected date and for ML and EF within a range of about ±6-7 days (see column (v)).

From the data in Tables 3a and 3b I conclude:

1. that in the traditional historical window 1710-1550 BC the Venus observations allow three pairs of candidate chronologies: Ammī-ṣaduqa year 1 = 1702/1694 BC, 1646/1638 BC and 1581/1574 BC,
2. that of these the 1646 BC, 1638 BC, the 1581 BC and the 1574 BC chronologies provide the best fit to the Venus data (standard deviations ≤ 3.9 days),
3. that the canonical High Middle Chronology (1646 BC) is less probable because the lunar calendar shift exceeds the standard deviation,
4. that the 1574 BC chronology proposed by Mebert (2010) is a valid candidate chronology,

[7] The one chronology for which observation no. 17 is within range is the 1550 BC chronology, proposed by Gasche *et al*. (1998). Table 3b shows that for this chronology all other observations are out of range.

[8] This may be illustrated by comparing the mean values of δd and the standard deviations in Tables 3a and 3b with the values in lines (5) and (6) of Table 2 in de Jong (2013) calculated for a somewhat extended set of Venus observations from which observations nos. 17 and 18 were omitted.

[9] Leaving aside the 1550 BC chronology which provides a poor fit to almost all observations.

5. that the 1550 BC chronology proposed by Gasche *et al*. (1998) is "not supported" by the Venus observations, and
6. that the Venus observations by themselves are insufficient to choose between the six candidate chronologies so that additional constraints are required to make a final choice.

The astronomical data that have been used in the past to try to make a choice between candidate Venus chronologies are: the distribution of 30-day months in the Old Babylonian calendar (Huber *et al*. 1982; Mebert 2010), a lunar eclipse reported by the diviner Asqūdum to the king of Mari (Banjevic 2006; Mebert 2010), and the record of a solar eclipse in the Mari Eponym Chronicle in the year after the birth of Šamši-Adad (Michel and Rocher 1997/2000; Mebert 2010).[10] However, so far all attempts to establish absolute dates for the Old Assyrian and Old Babylonian chronology have been been inconclusive (see the review by Pruzsinszky 2009).

4. *Month length statistics*

The chronological tool of month length statistics was first applied to the problem of the Old Babylonian chronology by Langdon *et al*. (1928) and later perfected by Huber *et al*. (1982). The Babylonian calendar uses the synodic lunar month as the basic unit of time. A synodic lunar month measures the number of days between the first evening visibility of the Moon (the new crescent) and the next one. It consists of 29 or 30 days, its length being determined by observation. This observation could be affected by bad weather or poor observational discipline so that 31-day months might in principle have occurred. However, apparently by convention, a month never contained more than 30 days. Errors of observation were automatically corrected at the beginning of the next month by observation of the next new crescent.

Due to the many irregularities in the Moon's motion the prediction of new crescent visibility is far from trivial. It took the Babylonians more than one millennium to finally tackle this problem (in the fourth century BC; see Neugebauer 1955, p. 41ff.). Nowadays dates of new crescent visibility can be reliably predicted using modern astronomical methods and algorithms (see Huber *et al*. 1982; Mebert 2010). It turns out that of all months in a lunar calendar 47% are 29-day months and 53% are 30-day months (because one synodic month lasts on average 29.53 days). By comparing 30-day month lengths attested in Neo-Babylonian administrative and economic texts with predicted month lengths Huber *et al*. (1982) found that the month length was correctly predicted in 67% of all cases (103 out of 153). This comparison can be made because the intercalation pattern of the Babylonian lunar calendar during the last six centuries BC is well known (Parker and Dubberstein 1956). To be able to use 30-day month length statistics as a tool to choose between different Old Babylonian candidate chronologies we clearly need: (1) to have a collection of attested 30-day months from Old Babylonian texts, and (2) to know the intercalation pattern of the lunar calendar.

From the existing literature Huber *et al*. (1982) collected 21 months of 30-day duration during the years Ammī-ṣaduqa 1-16 for which the intercalation pattern was known (corroborated by the Venus observations). Based on an analysis of these data they expressed strong

[10] I am not including here the lunar eclipse omina described in Tablets 20 and 21 of *Enūma Anu Enlil* which have been used by Gasche *et al*. (1998) and by Huber (2000) because they are probably not sufficiently historical to be of much use for chronology as argued by Hunger (2000).

preference for the Long Chronology (Ammī-ṣaduqa year 1 = 1702 BC) with 15 out of 21 month-lengths (71%) correctly predicted. The two Middle Chronologies were discarded because they scored only about 40% correct 30-day month lengths.

Recently Mebert (2010, p. 87-92 and 151-160) has repeated Huber *et al.*'s analysis based on a larger database of 37 months of 30-day duration distributed over 32 consecutive years (Ammī-ditāna years 22-37, immediately followed by Ammī-ṣaduqa years 1-16). Based on his analysis Mebert favours the 1574 BC chronology (70% score), with the Long Chronology (1702 BC) as runner-up (see Table 4). Mebert confirms Huber *et al.*'s conclusion that the Middle Chronologies can be discarded.

Since the month-length statistics hinges on the correct observation of the first visibility of the lunar crescent and on the assumption that it determines the beginning of the new month I investigate the robustness of the month length statistics as a tool to discriminate between chronologies in some detail below. First, I briefly review the Neo- and Late Babylonian textual material collected by Huber *et al.* (1982), recently updated and complemented by Mebert (2010), from which dates of first lunar crescent sightings and/or 30-day month lengths were extracted. These texts date from the period 650-50 BC (see Table 5.2 in Huber *et al.* 1982). They consist of:

1. Astronomical texts published by A.J. Sachs. These texts predominantly date from the last five centuries BC. From these texts a total of 602 lunar crescent observations could be extracted. Since these texts are from a period where the Babylonian calendar is known (Parker and Dubberstein 1956) the calendar can be compared with calculated lunar crescent sightings. It turns out that there are 34 discrepancies between observation and calculation (34/602 = 5.6%). Each crescent observation affects the month-length of a pair of two consecutive months. Assuming that no pair of affected months is consecutive this implies 11.2% discrepancies in 30-day month-length (misses) for a correct chronology.
2. Economic/administrative texts collected by A.J. Sachs and E. Leichty. These texts date predominantly from the seventh and sixth century BC. Huber *et al.* combined the two collections and showed that there are 50 disagreements between text and calculation (misses) in the total sample of 153 30-day months resulting in a miss rate of 30-day months of 50/153 = 32.7% for a correct chronology. Huber notes that this 32.7% miss rate is "uncomfortably close" to the 47% miss rate expected from comparison of a random distribution of 30-day months with calculated month-lengths.

Thus, during the last six centuries BC the calendar practice of the scribes of the administrative texts was considerably less accurate than that of the more scholarly scribes of *Enūma Anu Enlil* who wrote the astronomical texts.[11] This may be due to incompetence or observational nonchalance of the administrative scribe, poor weather conditions or calendar differences from city to city.

For the administrative texts of the Old Babylonian period Huber *et al.* adopt the same miss rate of 33% of 30-day months as found for the Neo-Babylonian period, implicitly assuming that the accuracy of the calendar is similar for both periods. I think that this may be overly optimistic because one would expect the accuracy of the calendar to have improved over a

[11] For a discussion of the duties of the *ṭupšar Enūma Anu Enlil*, see Rochberg (2004), p. 219ff.

timespan of more than one millennium.[12] For one thing, in Old Babylonian times the first day of the month was exclusively based on observation while from the seventh century BC onwards tools to correctly predict the first day of the month were available (based on periodicity in the so-called "lunar-six", see Huber and Steele 2007).

The astronomical texts collected by Huber *et al*. show 5.6% missed first crescent observations, corresponding to 11% wrong month-lengths, both of the 29-day months as well as of the 30-day months. Thus during the last five centuries BC the astronomical scribes made wrong first crescent observations/predictions in only about 1 out of 20 cases (corresponding to a miss rate of 2/20 = 10% in the 30-day month-lengths). In Neo- and Late Babylonian times the scribes writing the administrative texts used a calendar where the first crescent observation was apparently wrong in 1 out of 6 cases (30-day month-lengths miss rate of 2/6 = 33%). As suggested above, it seems probable that the calendar in Old Babylonian times may have been less accurate.

If the calendar used by the scribes in Old Babylonian times was based on an inaccurate determination of the day of first crescent visibility in 1 out of 5 cases, this would result in a miss rate of about 40% of the 30-day months. If the scribes would have used a calendar based on wrong crescent dates in 1 out of 4 cases about 50% of the month-lengths would be wrong.

Using the statistical formulation of Huber *et al*. (1982, p. 45) I show in columns (iii)-(v) and (vii)-(ix) of Table 5 the probabilities P for the candidate chronologies in column (i) to be the correct one. These probabilities are calculated for a calendar practice of decreasing accuracy characterized by 30-day month-length miss rates p = 0.33, 0.40 and 0.50, as discussed above. The calculations are carried out for two samples of 30-day month lengths: a sample of 24 months from Ammī-ṣaduqa years 1-16, and a sample of 37 months for the period Ammī-ditāna year 22 – Ammī-ṣaduqa year 16.

The data for both samples are taken from Mebert (2010) and are shown in Table 4. For both samples the numbers of 30-day months in the sample, the numbers of those 30-day months that are correctly determined as follows from comparison with calculation, and the corresponding percentages are listed for each candidate chronology. From these data the number of misses m shown in columns (ii) and (vi) of Table 5 can be directly derived.

From the data in Table 5 I conclude that:

1. the chronology favored by the month-length statistics (marked in bold face) depends on the size of the sample and on the accuracy of the lunar calendar,
2. for a reasonable accurate lunar calendar practice (at most one out of five first lunar crescent sightings wrong) the 1574 BC chronology is the favorite, and
3. for inaccurate lunar calendars (one out of four first crescent sightings wrong, or worse) the 30-day month length statistics looses its significance and is thus not suitable as a chronological tool.

Another implication of an Old Babylonian lunar calendar of limited accuracy is that the lunar dates of the Venus observations may have an uncertainty of order one day which would add to the standard deviations in the last entries of Tables 3a and 3b.

[12] W. Sallaberger (1993, p. 11-14) has shown that in the Ur III period, directly preceding the Old Babylonian period, the calendar practice must have been less accurate because the available texts indicate that there are years containing more 30-day months than astronomically possible.

5. The Šamši-Adad solar eclipse

In the Mari Eponym Chronicle a "darkening of the Sun" is mentioned around the birth of Šamši-Adad. The text has been generally interpreted as referring to the occurrence of a solar eclipse. There have been several attempts to date the birth of Šamši-Adad based on this solar eclipse (for a recent review see Roaf 2012). According to the text of the Mari Eponym Chronicle (Barjamovic *et al*. 2012, p. 32-33) the eclipse took place in the year after Šamši-Adad was born (eponym Puzur-Ištar, REL 127).[13] Using the chronological calibration of the Revised Eponym List (REL) by Barjamovic *et al.* I find that the time window in which the solar eclipse must have occurred can be constrained with 95% probability to the period 1856-1835 BC.[14] In Table 6 I show the maximum magnitudes[15] of all solar eclipses that took place in Assur (35° 27' N, 43° 16' E) between 1856 and 1835 BC for different values of the clock-time correction extrapolation error, ranging from -2 to +2 hours.

The eclipse data in Table 6 have been computed with a program that uses state-of-the-art astronomical ephemerides of the Sun (Bretagnon and Simon 1986) and the Moon (Chapront-Touzé and Chapront 1991) with modern values for the lunar secular acceleration and the clock-time correction implemented.[16] The eclipse predictions of this program have been checked against the *Five Millennium Catalog of Solar Eclipses: –1999 to +3000* by Espanak and Meeus (2009). The program has two unique features: (1) proper corrections for atmospheric refraction are applied near the horizon, and (2) extrapolation errors in the clock-time correction can be specified as a free parameter.

Atmospheric refraction causes noticeable displacements of the Sun and Moon near the horizon which may change the value of the eclipse magnitude by several hundredths up to one-tenth. This effect is not included in most predictions of solar eclipses in the literature.

Extrapolation errors in the clock-time correction represent the uncertainty in the gradual slowing down of the rate of rotation of the Earth which affects the exact location on Earth of the zone of totality of a solar eclipse and, consequently, also the magnitude of partial solar eclipses at geographical locations outside the zone of totality. The magnitude of the standard error in the clock-time correction during the second millennium BC has recently been estimated by Huber (2006, Table 3) based on an extrapolation of the errors in the clock-time corrections of well-documented historical eclipses during the first millennium BC taken from Morrison and Stephenson (1982). He estimates that around 1800 BC the 1σ error in the clock-time correction is of the order of 1 hour. This implies for the solar eclipses listed in Table 6

[13] Roaf (2012, p. 160) suggests that the incompleteness of the text of the Mari Eponym Chronicle allows a restoration such that the solar eclipse could have taken place during the year that Šamši-Adad was born (REL 126) rather than in the year after his birth (REL 127). However, according to Klaas Veenhof (private communication) there is a ruled line on the tablet before the entry in which the solar eclipse is mentioned so that there can be little doubt that the eclipse occurred in the eponymy of Puzur-Ištar (REL 127).

[14] This calibration is based on the assumption of Barjamovic *et al*. (2012, p. 29) that the timber used in the construction of the Waršama palace in Kanesh was cut right after the Old Palace was destroyed somewhere in the time span corresponding to REL 138-141. Based on radiocarbon dating of material from tree rings the felling of the trees from which the timber was cut has been dated to 1835/1832 BC +6/–8 yrs (Newton and Kuniholm 2004; Manning *et al*. 2010). This dating is quite accurate because on a large number of beams the bark has been preserved.

[15] The magnitude of a (partial) solar eclipse is defined as the fraction of the solar diameter covered by the Moon.

[16] For the lunar secular acceleration my program uses a value of –26 arcsec per century^2 based on lunar laser ranging measurements (Chapront *et al*. 2002) and for the clock-time correction it uses the relation $\Delta T = 32.5\ t^2$ sec (with t in centuries since 1800 AD) recommended by Huber (2000).

that the eclipse magnitudes in column (iv) (no extrapolation error) have a probability of about 40%, those for extrapolation errors of ±1 hr in columns (iii) and (iv) have a probability of about 25% and those computed for extrapolation errors of ±2 hrs in columns (ii) and (vi) have a probability of about 5%.

Partial solar eclipses will pass unnoticed for a naked-eye observer unless the Sun is more than about 95% eclipsed (Muller and Stephenson 1975, p. 467) or the eclipse happens very close to the horizon (within a few degrees) so that the Sun can be looked at without blinding the observer.[17] In Table 6 I have marked in boldface all eclipses with magnitudes larger than 0.95 and those at the horizon (R for sunrise or S for sunset) with magnitudes larger than 0.50. When a pair of numbers is listed in Table 6 the eclipse reaches its maximum after sunrise (the second number of the pair) or before sunset (the first number of the pair). In these cases the Sun is (already or still) so high above the horizon that the eclipse cannot be observed with the naked eye unless the magnitude exceeds 0.95.

Among the solar eclipses listed in Table 6 there are only three that qualify as possible candidates for the solar eclipse around the birth of Šamši-Adad. Below I give a detailed description of each of these three candidate solar eclipses computed for that value of the extrapolation error for which the eclipse reaches its largest magnitude:

1. 17 October 1849 BC (clock-time correction extrapolation error –1:55 hrs).[18] First contact at 12:13 hrs Local Time, totality (magnitude 1.01) at 13:35 hrs, duration about 1 minute, last contact at 14:55 hrs.
2. 5 August 1845 BC (clock-time correction error 1:15 hrs). First contact at 18:01 hrs, maximum magnitude (0.80) observable with the naked eye at 1.3° elevation above the horizon at 8 minutes before sunset, sunset (0.75 eclipsed) at 19:09 hrs.
3. 24 March 1838 BC (clock-time correction error 0:30 hrs). Sunrise during eclipse maximum (0.94) at 6:25 hrs, eclipsed (magnitude 0.92) and still observable with the naked eye at 1° elevation above the horizon 5 minutes after sunrise, last contact at 8:26 hrs.

This list of candidate eclipses will be used for the astronomical fine-tuning of the chronology in section 7.

Since Šamši-Adad was not born in Assur but most probabably near Eshnunna, where his family resided at the time, it is quite well possible that the solar eclipse around his birth was observed near Eshnunna, about 200 km South East of Assur. To investigate the effect of a different geographical location, I have repeated the calculations shown in Table 6 for Eshnunna (33° 45' N, 44° 45' E).[19] It turns out that the results are quite similar with eclipse magnitudes changing by at most a few hundredths of a magnitude compared to the magnitudes in Table 6.

6. A lunar eclipse reported by the diviner Asqūdum to the king of Mari

Mebert (2010, p. 105) mentions a lunar eclipse that is referred to in a letter of the diviner Asqūdum to the king of Mari (Durand 1988; letter no. 81, p. 221). He uses this eclipse to

[17] Cloud cover and dust storms may also incidentally allow partial eclipses to be observed.
[18] This eclipse becomes total for clock-time correction errors in the narrow range of –1:55 to –1:56 hrs.
[19] I owe this interesting suggestion to Gojko Barjamovic.

support his chronology proposal Ammī-ṣaduqa 1 = 1574 BC. Following Banjevic (2006) he assumes that the lunar eclipse was partial (based on a misreading of the text[20]) and that it took place in the eponym year which carries Asqūdum's name, corresponding to Hammurabi yr 11/12.

However, it turns out that on closer inspection[21] the latter assumption is unfounded because none of the known 65 letters of Asqūdum to the king of Mari are dated, including the one in which reference is made to a lunar eclipse (Charpin 2011). Moreover, Asqūdum served as diviner under two kings of Mari, first under Šamši-Adad's son Yasmah-Addu, and later, after Mari was conquered by Zimri-Lim, for the last eight years of his life as diviner and senior political adviser under Zimri-Lim (Charpin 2011). It is not clear whether the letter which refers to a lunar eclipse was addressed to Yasmah-Addu or Zimri-Lim. Heimpel (2003, p. 529) suggests that it was written to Zimri-Lim while Charpin (2011, p. 254) notes that "most of Asqūdum's letters that exclusively concern divination seem to date to Yasmah-Addu's time". Thus the time window in which the lunar eclipse occurred spans some 20 years which makes its astronomical dating impossible, even if we would limit ourselves to total lunar eclipses only.

7. Astronomical fine-tuning of the chronology of the Hammurabi age

My starting point for the astronomical fine-tuning process is the recent study of Barjamovic *et al*. (2012) who have been able to constrain the uncertainty margin in the absolute dating of the Old Assyrian chronology to about 20 years. This narrowing down is based on a revision of the Kültepe eponym list (REL) and on an absolute dating of this list based on radiocarbon dating of tree-ring sequences in wooden beams used for the building of the Waršama palace in Kanesh. According to Barjamovic *et al*. the Assyrian king Šamši-Adad died in REL 197 which corresponds to absolute time 1776 BC ± 10 years (at the 95% confidence level).

The first step in the fine-tuning of the Old Babylonian chronology is to make use of the well-established synchronism that Šamši-Adad died in the last month of the Assyrian year with eponym Ṭāb-ṣilli-Aššur (REL 197) during the 18th year of the Old Babylonian king Hammurabi (Charpin and Ziegler 2003, p.170ff.). According to Barjamovic *et al*. Šamši-Adad was born in REL 126 so that he died at the advanced age of 71 years. Based on this synchronism the date of the first year of the reign of Hammurabi is then constrained to 1793 BC ± 10 yrs. Using the well-established Old Babylonian relative chronology of the Hammurabi dynasty (e.g. Hunger and Pingree 1999, p. ix) this implies that the first year of the reign of king Ammī-ṣaduqa is constrained to 1647 BC ± 10 yrs, and the fall of Babylon to 1596 BC ± 10 yrs.[22] These much stricter limits to the absolute dating of the Old Babylonian chronology imply that of all the candidate chronologies allowed by the Venus observations only the two Middle Chronologies remain as viable candidates.

In Table 7 I give a chronological overview of about 250 years starting with the birth of Šamši-Adad and ending with the conquest of Babylon by the Hittite king Mursilis I. The chronological markers in column (i) are the REL numbers of Barjamovic *et al*. (2012) and/or

[20] For a translation of Asqūdum's letter see Heimpel (2003), p. 209 (Text 26 81).

[21] Following a suggestion by Klaas Veenhof.

[22] Assuming that Babylon fell in the last year of Samsu-ditāna's reign. According to Roaf (2012, p. 24) it is possible that Babylon was destroyed five years ealier.

the regnal years of kings of the Hammurabi dynasty. Column (ii) lists the REL eponym names taken from Barjamovic *et al*. and historical events that play a role in the absolute dating of the Old Assyrian and Old Babylonian chronologies. Columns (iii) and (iv) give absolute dates for the chronological markers in column (i) and for the historical events in column (ii) for the only two remaining candidate chronologies, the High and Low Middle Chronologies. For the calendar dates in columns (iii) and (iv) I have assumed that on average the Assyrian year starts near Winter Solstice[23] (about January 1) and the Old Babylonian year near Spring Equinox[24] (about April 1).

The building of the Waršama palace must have taken place after the Old Palace was destroyed sometime during the period covered by REL 138-141. According to the chronological scheme in Table 7 this destruction took place in 1834/1 BC for the High Middle Chronology or in 1826/3 BC for the Low Middle Chronology. Both ranges of dates fall within the 95% confidence radiocarbon window of 1835/32 BC +6/–8 yrs in which the timber used for the construction of the Waršama palace was cut (Newton and Kuniholm 2006; Manning *et al*. 2010). If indeed the Low Middle Chronology will turn out to be the correct one this implies that the timber used for the construction of the Waršama Palace may have been cut a few years before the destruction of the Old Palace. This would allow for transportation of trees to Kanesh and for drying of the wood before processing.

Before turning to the solar eclipse around the birth of Šamši-Adad as a potential tool for fine-tuning the chronology of the Hammurabi age it is of interest to briefly discuss the accuracy of the revision of the Kültepe Eponym List during the time span covering the life of Šamši-Adad (REL 126-197). One uncertainty, extensively discussed by Barjamovic *et al.* (2012, p. 9ff.), concerns the eponymy of Ahiyaya (REL 193), recently also put into doubt by Liebich (2012).[25] If indeed we could do away with the eponym of Ahiyaya, because in some way or other he held a co-eponymy with another official, this would shift the birth year of Šamši-Adad one year forward in absolute time because his death is anchored to the Venus observations through Hammurabi. On the other hand Veenhof (2007) has presented arguments in favour of shifting the birth of Šamši-Adad a few years backwards in time. He points out that according to the *Distanzangaben* the time interval between the accession year of Erišum I and the death of Šamši-Adad equals 199 years while according to the REL it is 196 years. This implies that Šamši-Adad would have died at the age of 74 rather than at 71 so that he may have been born three years earlier. For the discussion below I will adopt an uncertainty margin of ±2 years in the birth date of Šamši-Adad.

Taking this margin into account I find from the chronological overview in Table 7 that the solar eclipse around the birth of Šamši-Adad must have taken place in 1845 BC ± 2 yrs (High Middle Chronology) or in 1837 BC ± 2 yrs (Low Middle Chronology). The data in Table 6 show that there are indeed candidate eclipses for both chronologies which may qualify as solar eclipses causing a "darkening of the Sun", the partial eclipse of 5 August 1845 BC and the one of 24 March 1838 BC. On the basis of these solar eclipses there are two reasons to express preference for the Low Middle Chronology: (1) the 1838 BC eclipse is the most conspicuous one (0.94 magnitude at the horizon versus 0.75), and (2) the 1838 BC eclipse requires

[23] See Dercksen (2011).
[24] See Mebert (2010), p. 93ff.
[25] I thank Yigal Bloch for bringing this to my attention.

a much smaller clock-time correction error (0:30 versus 1:15 hrs, equivalent to about 0.5 versus 1.25σ) which makes it about twice more probable. If the Low Middle Chronology indeed turns out to be the correct one the data in Table 7 imply that the birth of Šamši-Adad (REL 126) needs to be pushed backward one year in time[26] so that an additional eponym is required between REL 127 and 197.

It is of interest to note that the most spectacular candidate eclipse, the total solar eclipse of 24 June 1833 BC (Michel and Rocher 1999), while only reconcilable with the Low Middle Chronology, would require that the Revised Eponym List be inflated by about four years during the roughly 70 years spanning the lifetime of Šamši-Adad (REL 126-197) which seems more than allowed by the present uncertainties.

Based on the fine-tuning process presented in this section I suggest that the Low Middle Chronology is the correct one for the history of Mesopotamia between 1963 BC (REL 1, the accession year of the Old Assyrian king Erišum I) and 1587 BC (the conquest of Babylon by the Hittite king Mursilis I). My arguments for this choice are threefold:

1. The Low Middle Chronology provides a better fit to the Venus observations as reflected in the mean deviation to the lunar calendar of –0.4 days for the Low Middle Chronology versus –4.3 days (exceeding the standard mean error) for the High Middle Chronology (see Table 3b). Now that the possible candidate Venus chronologies have been reduced to two this is a much stronger argument than when one had to choose between six Venus chronologies.
2. Although for both Middle Chronologies a solar eclipse can be identified that might be responsible for the "darkening of the Sun" mentioned in the Mari Eponym Chronicle, I prefer the Low Middle Chronology eclipse candidate of 24 March 1838 BC because it is more conspicuous (magnitude 0.94 at the horizon versus 0.80) and the clock-time correction extrapolation error is more than two times smaller making it twice more probable.
3. The Low Middle Chronology also provides a natural explanation for the enhanced atmospheric extinction in Babylon, inferred from the Venus observations during years 12 and 13 of the reign of king Ammī-ṣaduqa. De Jong and Foertmeyer (2010) have argued that this enhancement was caused by aerosols expelled into the Earth atmosphere by the violent eruption of the volcano on the Greek island Thera (present-day Santorini). The eruption has been radiocarbon dated to 1613 BC +14/–13 yrs (at the 95% confidence level) by Friedrich *et al*. (2006) based on tree-ring sequences in the remains of several olive branches found in layers of pumice left by the eruption. De Jong and Foertmeyer show that this dating can only be reconciled with the affected Venus observations if the Low Middle Chronology is adopted leading to a date for the eruption in 1628/27 BC.

7. Conclusions

Combining the radiocarbon dating of tree-ring sequences in beams used in the construction of the Waršama palace in Kanesh with the chronological constraints provided by the Venus observations during the reign of the Babylonian king Ammī-ṣaduqa and by the solar eclipse around the birth of the Assyrian king Šamši-Adad I have shown that most probably the Low

[26] This would increase the lifetime of Šamši-Adad to 72 years.

Middle Chronology (Ammī-ṣaduqa 1 = 1638 BC) is the correct one for the Old Assyrian and Old Babylonian period.[27]

If the Low Middle Chronology is indeed the correct chronology for the Hammurabi age one may conclude in hindsight that the (High) Middle Chronology, that has been used by Assyriologists for the last 50 years, was an excellent educated guess by being only 8 years too early, that the Long Chronology (Ammī-ṣaduqa 1 = 1702 BC) proposed by Huber *et al*. (1982) was 64 years too early, that the Ultra Short Chronology (Ammī-ṣaduqa 1 = 1550 BC) proposed by Gasche *et al*. (1998) as a serious alternative to the Middle Chronology, was too late by 88 years, and that the recent chronology proposal (Ammī-ṣaduqa 1 = 1574 BC) of Mebert (2010) is 64 years too late.

Both Mebert's chronology proposal and the Long Chronology heavily rest on the comparison of attested months of 30-day duration with predicted month lengths. The fact that both proposals violate the radiocarbon dating constraints may be considered as evidence that the calendar practice in Old Babylonian times was of limited accuracy so that the 30-day month length statistics does not seem to be an adequate chronological tool.

Acknowledgements

I would like to thank Gojko Barjamovic, Yigal Bloch and Peter Huber for stimulating discussions and correspondence and in particular Michael Roaf and Klaas Veenhof for a critical reading of earlier versions of this paper as well as several very useful suggestions for its improvement.

Bibliography

Banjevic, B. 2006. Ancient Eclipses and Dating the Fall of Babylon, *Publications of the Astronomical Observatory of Belgrade* 80, 251-257.

Barjamovic, G., Hertel, T. and Larsen, M.T. 2012. *Ups and Downs at Kanesh*, Nederlands Instituut voor het Nabije Oosten, Leiden.

Bretagnon, P. and Simon, J.L. 1986. *Planetary Programs and Tables from –4000 to +2800*, Willman-Bell Inc., Richmond.

Bruins, H.J., MacGillivray, J.A., Synolakis, C.E., Benjamini, C., Keller, J., Kisch, H.J., Klügel, A., and van der Plicht, J. 2008. Geoarcheological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini, *Journal of Archeological Science* 35, 191-212.

Chapront, J., Chapront-Touzé, M. and Francou, G. 2002. A new determination of lunar orbital parameters, precession constant and tidal acceleration from LLR measurements, *Astronomy and Astrophysics* 387, 700-709.

Chapront-Touzé, M. and Chapront, J. 1991. *Lunar tables and programs from 4000 B.C. to A.D. 8000*, Willmann-Bell Inc., Richmond.

Charpin, D. 2011, Patron and Client: Zimri-Lim and Asqudum the diviner, in *The Oxford Handbook of Mesopotamian Culture*, K. Radner and E. Robson eds., Oxford.

[27] When the writing of this paper was in its final stage I received a copy of a paper by W. Nahm, entitled "The case for the Lower Middle Chronology" (to appear in *Altorientalische Forschungen*), in which the author reaches similar conclusions. In response to the first draft of this paper W. Sallaberger was so kind to send me an excerpt from a manuscript by W. Sallaberger and I. Schrakamp entitled "Philological Data for a Historical Chronology of Mesopotamia in the 3rd Millennium" to appear in *ARCANE* vol. III (see http://www.arcane.uni-tuebingen.de) in which the authors make a case for a chronology lowered by 5 years compared to the Low Middle Chronology.

Charpin, D. and Ziegler, N. 2003. Mari et le Proche-Orient à l'époque amorrite: essai d'histoire politique, *Florilegium Marianum* V, Paris.
Dercksen, J.G. 2011. The beginning of the Old Assyrian year, *Nouvelles Assyriologiques Brèves et Utilitaires* 2011, no. 74.
Durand, J.-M. 1988. Archives Épistolaires de Mari I/1, *Archives Royales de Mari* XXVI-1, Paris.
Espanak, F. and Meeus, J. 2009. http://eclipse.gsfc.nasa.gov/SEcat5/SEcatalog.html.
Friedrich, W.L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T., and Talamo, S. 2006. Santorini Eruption Radiocarbon Dated to 1627-1600 B.C., *Science* 312, 548.
Gasche, H. et al. 1998. *Dating the Fall of Babylon. A Reappraisal of the Second-Millennium Chronology*, Ghent.
Heimpel, W. 2003. *Letters to the King of Mari*, Eisenbrauns, Winona Lake.
Huber, P.J. 2000. Astronomy and Ancient Chronology, *Akkadica* 119/120, 159-176
Huber, P.J. 2006. Modeling the length of day and extrapolating the rotation of the Earth, *Journal of Geodesy* 80, 283-303.
Huber, P.J. 2011. Review of Mebert, Joachim: Die Venustafeln des Ammī-ṣaduqa und ihre Bedeutung für die astronomische Datierung der altbabylonischen Zeit, *Zeitschrift für Assyriologie* 101, 309-314.
Huber, P.J. and Steele, J.M. 2007. Babylonian Lunar Six Tablets, *SCIAMVS* 8, 3-36.
Huber, P.J., Sachs, A., Stol, M., Whiting, R.M., Leichty, E., Walker, C.B.F. and van Driel, G. 1982. *Astronomical Dating of Babylon I and Ur III*, Undena Publications, Malibu.
Hunger, H. 2000. Uses of Enūma Anu Enlil for Chronology, *Akkadica* 119/120, 155-158.
Hunger, H. 2009. How uncertain is Mesopotamian chronology?, in *Time's up! Dating the Minoan eruption of Santorini*, D.A. Warburton ed., Aarhus University Press, 145-152.
Hunger, H. and Pingree, D. 1989. MUL.APIN: An Astronomical Compendium in Cuneiform, *Archiv für Orientforschung, Beiheft 24*, Vienna.
Hunger, H. and Pingree, D. 1999. *Astral Sciences in Mesopotamia*. Brill, Leiden.
de Jong, T. 2012. Babylonian observations of Venus: arcus visionis, atmospheric extinction and observational practice, *Journal for the History of Astronomy* 43, 391-409.
de Jong, T. 2013. Review of Mebert, Joachim: Die Venustafeln des Ammī-ṣaduqa und ihre Bedeutung für die astronomische Datierung der altbabylonischen Zeit, *Journal of the American Oriental Society* 133, in press.
de Jong, T. and Foertmeyer, V. 2010. A New Look at the Venus Observations of Ammisaduqa: Traces of the Santorini Eruption in the Atmosphere of Babylon?, *Jaarbericht "Ex Oriente Lux"* 42, 143-159.
Kugler, F.X. 1912. *Sternkunde und Sterndienst in Babel II, Teil II, Heft 1*, Münster.
Liebich, M. 2012, Die Eponymenliste KEL G und Distanzangaben assyrischer Bauinschriften, *Nouvelles Assyriologiques Brèves et Utilitaires* 2012, no. 45.
Manning, S.W., Kromer, B., Kuniholm, P.I. and Newton, M.W. 2001. Anatolian Tree Rings and a New Chronology for the East Mediterranean Bronze-Iron Ages, *Science* 294, 2532-2535.
Manning, S.W., Kromer, B., Ramsey, C.B., Pearson, C.L., Talamo, S., Trano, N. and Watkins, J.D. 2010. ^{14}C record and wiggle-match placement for the Anatolian (Gordion Area) Juniper tree-ring chronology ~ 1729 to 751 CAL BC, and typical Aegean/Anatolian (growing season related) regional ^{14}C offset assessment, *Radiocarbon* 52/4, 1571-1597.
Mebert, J. 2010. Die Venustafeln des Ammi-ṣaduqa und ihre Bedeutung fur die astronomische Datierung der altbabylonische Zeit, *Archiv für Orientforschung, Beiheft* 31, Vienna.
Michel, C. and Rocher, P. 1997-2000. La Chronologie du IIe millénaire revue à l'Ombre d'une Éclipse de Soleil, *Jaarbericht "Ex Oriente Lux"* 35-36, 111-126.
Morrison, L.V. and Stephenson, F.R. 1982, Secular and decade fluctuations in the Earth's rotation, in *Sun and Planetary Systems*, W. Fricke and G. Teleski eds., Reidel, Dordrecht.
Muller, P.M. and Stephenson, F.R. 1975. The acceleration of the Earth and Moon from early astronomical observations, in *Growth Rhythms and the History of the Earth's Rotation*, G.D. Rosenberg and S.K. Runcorn eds., London, 459-533.
Neugebauer, O. 1941. The Chronology of the Hammurabi Age, *Journal of the American Oriental Society* 61, 58-61.

Neugebauer, O. 1955. *Astronomical Cuneiform Texts*, vol. I, London.
Newton, M.W. and Kuniholm, P.I. 2004. A Dendrochronological Framework for the Assyrian Colony Period in Asia Minor, *Türkiye Bilimler Akademisi Arkeoloji Dergisi* 7, 165-176.
Parker, R.A. and Dubberstein, W.H. 1956. *Babylonian Chronology 626 B.C. – AD 75*, Providence.
Pruzsinszky, R. 2009. *Mesopotamian Chronology of the 2nd Millennium B.C. An Introduction to the Textual Evidence and Related Chronological Issues*, Vienna.
Reiner, E. and Pingree, D. 1975. *Babylonian Planetary Omens I, Enūma Anu Enlil, Tablet 63: The Venus Tablet of Ammisaduqa*, Undena Publications, Malibu.
Roaf, M. 2012, The Fall of Babylon in 1499 BC or 1595 BC, *Akkadica* 133, 147-174.
Rochberg, F. 2004. *The Heavenly Writing*, Cambridge.
Sallaberger, W. 1993, *Der kultische Kalender der Ur III-Zeit*, Untersuchungen zur Assyriologie und vorderasiatischen Archäologie vol. 7, De Gruyter, Berlin
Veenhof, K.R. 2007. The Old Assyrian List of Year Eponyms. Corrections, Additions and Chronology. *Nouvelles Assyriologiques Brèves et Utilitaires* 2007, no. 49.
van der Waerden, B.L. 1945/48. On Babylonian Astronomy I. The Venus Tablets of Ammisaduqa, *Jaarbericht "Ex Oriente Lux"* 10, 414-424.
Weir, J.D. 1972, *The Venus Tablet of Ammizaduqa*, Uitgaven van het Nederlands Historisch-Archeologisch Instituut te Istanbul xxix, Istanbul.

Table 1. The first appearance of Venus in the early morning of 18 *Šabatu* (month XI) year 1 of Ammī-ṣaduqa (observation nr. 2) for all possible Venus chronologies between 1710 and 1550 BC.

Chronology	Amṣdq yr 1	Observed date	Computed date		δd
	Julian year	Julian date	Julian date	Bab day	days
	1710 BC	27-Mar 1709 BC	3-Apr	25	-7
Long	1702 BC	28-Mar 1701 BC	31-Mar	21	-3
	1694 BC	29-Mar 1693 BC	29-Mar	18	0
	1686 BC	31-Mar 1685 BC	26-Mar	13	5
	1678 BC	1-Apr 1677 BC	24-Mar	10	8
	1670 BC	3-Apr 1669 BC	21-Mar	5	13
	1662 BC	6-Mar 1661 BC	19-Mar	2	-13
	1654 BC	8-Mar 1653 BC	16-Mar	26	-8
High Middle	1646 BC	9-Mar 1645 BC	14-Mar	23	-5
Low Middle	1638 BC	11-Mar 1637 BC	11-Mar	18	0
	1630 BC	13-Mar 1629 BC	9-Mar	14	4
	1622 BC	14-Mar 1621 BC	6-Mar	10	8
	1614 BC	15-Mar 1613 BC	4-Mar	7	11
	1606 BC	17-Mar 1605 BC	2-Mar	3	15
	1598 BC	17-Feb 1597 BC	28-Feb	29	-11
	1590 BC	19-Feb 1589 BC	26-Feb	25	-7
Short	1582 BC	20-Feb 1581 BC	24-Feb	22	-4
Mebert	1574 BC	22-Feb 1573 BC	21-Feb	17	1
	1566 BC	24-Feb 1565 BC	19-Feb	13	-5
	1558 BC	26-Feb 1557 BC	17-Feb	9	9
Gasche *et al.*	1550 BC	27-Feb 1549 BC	14-Feb	5	13
(i)	(ii)	(iii)	(iv)	(v)	(vi)

Table 2. Visibility parameters of Venus (adapted from de Jong 2012).

Observation	h_0 [°]	σ [°]	δh/day [°/day]	δday (95%) [days]
Evening Last	5.2	1.9	1.08	3.5
Morning First	8.0	1.5	1.07	2.8
Morning Last	5.9	0.7	0.20	7.1
Evening First	6.7	0.7	0.23	6.1
(i)	(ii)	(iii)	(iv)	(v)

Table 3a. Fits to the first 20 Venus observations and overall quality of fit for candidate Venus chronologies 1710-1600 BC.

Ammī-ṣaduqa yr 1 =						1702 BC				1694 BC				1646 BC				1638 BC			
Text [RP75]						Observed		Comp		Observed		Comp		Observed		Comp		Observed		Comp	
nr	Yr	Mo	Bd	Obs	Bd'	Julian	date	Bd	δd	Julian	date	Bd	δd	Julian	date	Bd	δd	Julian	date	Bd	δd
1	1	XI	15	EL	14	23-Mar	-1700	15	-1	24-Mar	-1692	12	2	4-Mar	-1644	18	-4	6-Mar	-1636	14	0
2	1	XI	18	MF	18	28-Mar	-1700	21	-3	29-Mar	-1692	18	0	9-Mar	-1644	23	-5	11-Mar	-1636	18	0
3	2	VIII	11	ML	10	11-Dec	-1700	17	-7	13-Dec	-1692	13	-3	22-Nov	-1644	20	-10	23-Nov	-1636	17	-7
4	2	X	19	EF	19	16-Feb	-1699	18	1	18-Feb	-1691	14	5	28-Jan	-1643	22	-3	29-Jan	-1635	19	0
5	3	VI	23	EL	22	13-Oct	-1699	29	-7	15-Oct	-1691	24	-2	24-Sep	-1643	28	-6	26-Sep	-1635	23	-1
6	3	VII	13	MF	13	4-Nov	-1699	16	-3	5-Nov	-1691	12	1	16-Oct	-1643	17	-4	17-Oct	-1635	14	-1
7	4	IV	2	ML	1	15-Jul	-1698	9	-8	17-Jul	-1690	4	-3	26-Jun	-1642	9	-8	28-Jun	-1634	4	-3
8	4	VI	3	EF	3	13-Sep	-1698	17	-14	15-Sep	-1690	12	-9	26-Aug	-1642	13	-10	27-Aug	-1634	9	-6
9	5	II	2	EL	1	4-Jun	-1697	27	3	6-Jun	-1689	24	7	16-May	-1641	1	0	18-May	-1633	27	4
10	5	II	18	MF	18	22-Jun	-1697	13	5	24-Jun	-1689	8	10	3-Jun	-1641	15	3	5-Jun	-1633	11	7
11	5	IX	25	ML	24	19-Feb	-1696	20	4	21-Feb	-1688	17	7	1-Feb	-1640	25	-1	2-Feb	-1632	22	2
12	5	XI	29	EF	29	23-Apr	-1696	1	-1	24-Apr	-1688	26	3	3-Apr	-1640	4	-5	5-Apr	-1632	1	-1
13	6	VIII	28	EL	27	11-Jan	-1695	28	-1	12-Jan	-1687	24	3	24-Dec	-1640	29	-2	25-Dec	-1632	25	2
14	6	IX	1	MF	1	16-Jan	-1695	2	-1	17-Jan	-1687	28	3	28-Dec	-1640	5	-4	29-Dec	-1632	1	0
15	7	V	21	ML	20	29-Sep	-1695	25	-5	30-Sep	-1687	21	-1	9-Sep	-1639	28	-8	11-Sep	-1631	23	-3
16	7	VIII	2	EF	2	7-Dec	-1695	7	-5	8-Dec	-1687	4	-2	19-Nov	-1639	10	-8	20-Nov	-1631	7	-5
17	8	IV	25	EL	24	22-Aug	-1694	7	[17]	24-Aug	-1686	2	[22]	2-Aug	-1638	12	[12]	4-Aug	-1630	8	[16]
18	8	V	2	MF	2	31-Aug	-1694	25	7	1-Sep	-1686	21	10	11-Aug	-1638	29	3	13-Aug	-1630	25	7
19	8	XII	25	ML	24	16-Apr	-1693	29	-5	17-Apr	-1685	25	-1	29-Mar	-1637	29	-5	30-Mar	-1629	26	-2
20																					
									-2.3 ± 5.2				1.7 ± 4.9				-4.3 ± 3.9				-0.4 ± 3.9

Table 3b. Fits to the first 20 Venus observations and overall quality of fit for candidate Venus chronologies 1600-1550 BC.

Ammī-ṣaduqa yr 1 =						1582 BC				1574 BC				1550 BC			
Text [RP75]						Observed		Comp		Observed		Comp		Observed		Comp	
nr	Yr	Mo	Bd	Obs	Bd'	Julian	date	Bd	δd	Julian	date	Bd	δd	Julian	date	Bd	δd
1	1	XI	15	EL	14	15-Feb	-1580	18	-4	17-Feb	-1572	14	0	22-Feb	-1548	2	12
2	1	XI	18	MF	18	20-Feb	-1580	22	-4	22-Feb	-1572	17	1	27-Feb	-1548	5	13
3	2	VIII	11	ML	10	5-Nov	-1580	18	-8	6-Nov	-1572	14	-4	11-Nov	-1548	2	8
4	2	X	19	EF	19	10-Jan	-1579	23	-4	12-Jan	-1571	19	0	17-Jan	-1547	8	11
5	3	VI	23	EL	22	8-Sep	-1579	23	-1	8-Sep	-1571	21	1	13-Sep	-1547	9	13
6	3	VII	13	MF	13	29-Sep	-1579	15	-2	30-Sep	-1571	11	2	5-Oct	-1547	29	14
7	4	IV	2	ML	1	9-Jun	-1578	2	-1	10-Jun	-1570	27	3	15-Jun	-1546	12	18
8	4	VI	3	EF	3	9-Aug	-1578	6	-3	10-Aug	-1570	3	0	15-Aug	-1546	19	14
9	5	II	2	EL	1	29-Apr	-1577	30	1	30-Apr	-1569	26	4	5-May	-1545	14	16
10	5	II	18	MF	18	17-May	-1577	12	6	18-May	-1569	8	10	23-May	-1545	24	23
11	5	IX	25	ML	24	15-Jan	-1576	27	-3	17-Jan	-1568	23	1	20-Jan	-1544	14	10
12	5	XI	29	EF	29	18-Mar	-1576	3	-3	19-Mar	-1568	29	0	23-Mar	-1544	18	11
13	6	VIII	28	EL	27	6-Dec	-1576	25	2	9-Dec	-1568	19	8	13-Dec	-1544	7	20
14	6	IX	1	MF	1	11-Dec	-1576	3	-2	13-Dec	-1568	28	2	17-Dec	-1544	17	13
15	7	V	21	ML	20	22-Aug	-1575	26	-6	24-Aug	-1567	22	-2	29-Aug	-1543	10	10
16	7	VIII	2	EF	2	31-Oct	-1575	10	-8	3-Nov	-1567	5	-3	7-Nov	-1543	22	9
17	8	IV	25	EL	24	17-Jul	-1574	11	[13]	18-Jul	-1566	8	[16]	23-Jun	-1542	26	[-2]
18	8	V	2	MF	2	25-Jul	-1574	27	5	26-Jul	-1566	24	7	31-Jul	-1542	13	19
19	8	XII	25	ML	24	11-Mar	-1573	30	-6	13-Mar	-1565	26	-2	17-Mar	-1541	15	9
20																	
									-2.3 ± 3.9				1.6 ± 3.7				13.5 ± 4.2

Table 4. Comparison of month length statistics for the main candidate chronologies.

Chronology Ammī-ṣaduqa yr 1 =	Long 1702 BC	1694 BC	High Middle 1646 BC	Low Middle 1638 BC	Short 1582 BC	Mebert 1574 BC
Ammī-ditāna yrs 22-37						
30-day months attested	13	13	13	13	13	13
correctly predicted	5	7	7	5	5	10
% correct	38	54	54	38	38	**77**
Ammī-ṣaduqa yrs 1-16						
30-day months attested	24	24	24	24	24	24
correctly predicted	18	10	10	11	13	16
% correct	**75**	42	42	46	54	67
Total %	62	46	46	43	49	**70**

Table 5. Probabilities P that one of the chronologies is the correct one for three different assumptions about the accuracy of calendar keeping (miss rates p).

Chronology Amṣdq yr 1	P[Ammī-ṣaduqa]				P[Ammī-ṣaduqa & Ammī-ditāna]			
	m	p = 0.33	p = 0.40	p = 0.50	m	p = 0.33	p = 0.40	p = 0.50
1702 BC	6	**0.72**	**0.47**	0.09	14	0.14	0.24	0.10
1694 BC	14	0.01	0.05	**0.22**	20	0.00	0.04	0.21
1646 BC	14	0.01	0.05	**0.22**	20	0.00	0.04	0.21
1638 BC	13	0.01	0.06	0.20	21	0.00	0.03	**0.23**
1582 BC	11	0.04	0.11	0.16	19	0.01	0.06	0.18
1574 BC	8	0.22	0.26	0.11	11	**0.84**	**0.58**	0.07
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)

Table 6. All solar eclipses that took place in Assur between 1856 and 1835 BC.

δ(ΔT) [hrs]	-2	-1	0	1	2
Julian Date	Eclipse magnitude				
30/12/1853 BC	0.43	0.42	0.53	0.71	R0.28-0.91
14/06/1851 BC	0.09	—	—	—	—
17/10/1849 BC	**0.99**	0.77	0.49	0.24	0.05
13/04/1848 BC	0.48	0.29	0.04	—	—
02/04/1847 BC	0.11	0.27	0.50	0.77	0.91
17/08/1846 BC	—	S0.12	—	—	—
05/08/1845 BC	—	—	S0.07	**S0.79**	0.86-S0.20
05/06/1842 BC	0.15	R0.16-0.30	R0.30	—	—
24/03/1838 BC	0.87	0.94	**R0.55-0.95**	**R0.57**	—
12/03/1837 BC	0.25	0.08	—	—	—
26/08/1836 BC	0.22	R0.02-0.31	R0.45	R0.08	—
(i)	(ii)	(iii)	(iv)	(v)	(vi)

Table 7. Fine-tuning of the chronology of the Hammurabi age.

Chronological marker	Eponym/Event	High Middle Chronology Julian date	Low Middle Chronology Julian date
REL 126	Dādiya s. Šu-Ilabrat	1-Jan 1846 BC	1-Jan 1838 BC
	Šamši-Adad birth	1846 BC	1838 BC
	Solar eclipse candidate		24-Mar 1838 BC
REL 127	Puzur-Ištar s. Nūr-ilīšu	1-Jan 1845 BC	1-Jan 1837 BC
	Solar eclipse candidate	5-Aug 1845 BC	
REL 138	Ennam-Aššur	1-Jan 1834 BC	1-Jan 1826 BC
	Destruction of the Old Palace in Kanesh	1834/1 BC	1826/3 BC
REL 141	Šarrum-Adad	1-Jan 1831 BC	1-Jan 1823 BC
Hammurabi yr 1		1-Apr 1792 BC	1-Apr 1784 BC
REL 197	Ṭāb-ṣilli-Aššur	1-Jan 1775 BC	1-Jan 1767 BC
Hammurabi yr 18		1-Apr 1775 BC	1-Apr 1767 BC
	Šamši-Adad death	Dec 1775 BC	Dec 1767 BC
Ammī-ṣaduqa yr 1		1-Apr 1646 BC	1-Apr 1638 BC
Samsu-ditāna yr 31		1-Apr 1595 BC	1-Apr 1587 BC
	Sack of Babylon	1595 BC	1587 BC
(i)	(ii)	(iii)	(iv)