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A NEW LOOK AT THE VENUS OBSERVATIONS OF AMMISADUQA: TRACES OF THE SANTORINI ERUPTION IN THE ATMOSPHERE OF BABYLON?

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Abstract

The chronology of the ancient Near East (2000-1500 B.C.) is not well established. A much debated anchor point for this chronology is provided by a series of observed dates of the first appearance and the disappearance of the planet Venus during the reign of the Babylonian king Ammisaduqa. The Venus observations allow four different chronologies: Ammisaduqa year 1 = 1702 B.C. (the Long Chronology), 1646 and 1638 B.C. (the High and Low Middle Chronologies), and 1582 B.C. (the Short Chronology). In this paper we reanalyse the Venus observations using a physical model of the visibility of Venus in a twilight atmosphere. Although there are small differences between the quality of fit for the four different chronologies, the results do not allow us to make a decisive choice. This is reflected in the average visual extinction in the atmosphere of Babylon which varies from 0.25 ± 0.07 to 0.28 ± 0.11 magnitudes per airmass for the four different Venus chronologies. These extinction values are identical (within the standard deviations) to those found in earlier studies based on first and last appearances of stars and planets in Babylon in the 13th and 7th century B.C. The analysis further shows that there is a cluster of observations with enhanced extinction values in the 12th and 13th years of the reign of Ammisaduqa. These observations were discarded in previous studies as corrupted by scribal errors. In this paper we attribute these enhanced extinction values to the eruption of the volcano on the Greek island Thera (present-day Santorini). From the magnitude of the excess extinction we find that about 45 Megatons of aerosols were ejected into the Earth stratosphere in the eruption, and that the strength of the eruption was comparable to that of Krakatau (Indonesia, 1883). The Santorini eruption serves as an important calibration point for the Aegean Late Bronze Age chronology (1700-1400 B.C.). By connecting the chronologies of the ancient Near East and of the Aegean Late Bronze Age in this way, we are able to show that there are two possibilities: (i) the eruption occurred in 1628/1627 B.C., consistent with the radiocarbon dating window of the eruption, supporting the Low Middle Chronology of the ancient Near East (Ammisaduqa 1 = 1638 B.C.), or (ii) the eruption occurred in 1692/1691 B.C. when we adopt the Long Chronology of the ancient Near East (Ammisaduqa 1 = 1702 B.C.) based on the Old Babylonian month length calibration.

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I. Introduction

People in ancient Mesopotamia believed that the gods would indicate future events to mankind. These indications were called "signs" or omina. They could be found in the entrails of sacrificial animals, in the shapes of oil spreading on the surface of water, in phenomena observed in the sky, in strange occurrences in everyday life. Most omina are formulated as conditional clauses: "If x happens, then y will happen". The first part is called the protasis, the second part the apodosis. In the first millennium B.C. celestial omina are found organized in a series of about seventy tablets, called *Enūma Anu Enlil* after the opening words of its mythological introduction. The oldest material contained in this compendium dates from Old Babylonian times.[3]

Tablet 63 of *Enūma Anu Enlil* contains omina associated with the first appearance and disappearance of the planet Venus. The most recent edition by Reiner and Pingree (1975) of the cuneiform text of Tablet 63 is based on 15 sources, none of them complete and dating to the Neo-Assyrian or later periods. To illustrate the nature of the text we quote the first omen:

> "In month XI, 15th day, Venus in the west disappeared, 3 days in the sky it stayed away, and in month XI, 18th day, Venus in the east became visible: springs will open, Adad his rain, Ea his floods will bring, king to king messages of reconciliation will send."

The number of observations of Venus in the text amount to at least 40 and cover at least 16 years (two 8-year Venus periods); the apodoses may have been added later.

It was the Jesuit Franz Xaver Kugler[4] who realized in 1912 that the Venus observations could be used for chronological purposes because in omen nr. 10 reference is made to the "year of the Golden Throne", which is the year formula for the eighth year of the reign of the Old Babylonian king Ammisaduqa, the great-great-grandson of Hammurabi. Since then many authors have tried to use these observations to determine a chronology for the ancient Near East by fitting them to computed dates of first appearances and disappearances of Venus. In spite of all efforts the matter remains undecided and controversial.[5]

Ever since van der Waerden published his analysis of the Venus observations in *Jaarbericht "Ex Oriente Lux"* in 1948, it has been clear that fitting the Venus observations allows several different chronologies for the Old Babylonian king lists: a Long Chronology (Ammisaduqa 1 = 1702 B.C.), two Middle Chronologies (1646/1638 B.C.) and a Short Chronology (1582 B.C.). Other independent historical and/or archaeological evidence is required to choose among these chronologies. Over the past century there has been a continuous debate among specialists to try to settle this chronological question.[6] Important landmarks in the discussion were provided by the new edition of tablet 63 of *Enūma Anu Enlil* by Reiner and Pingree (1975) and the thorough reanalysis of Huber et al. (1982) of the Venus observations. Huber et al. confirmed and considerably strengthened the original results of van der Waerden, and based on an

[3] Hunger and Pingree 1999, 12-20
[4] Kugler 1912, 280
[5] see the proceedings of the colloquium *Just in Time* 2000
[6] Hunger & Pingree 1999, 32-40

extensive statistical analysis of the Venus data and of Old Babylonian month lengths they made a strong case for the Long Chronology.

The most recent effort in this area has been the work of Gasche et al. (1998), who proposed an Ultrashort Chronology with Ammisaduqa 1 = 1550 B.C., which can be more comfortably reconciled with the archaeological evidence. However, Huber (2000) has shown unambiguously that this chronology is inconsistent with and in fact is refuted by the Venus observations.

Support for the (Low) Middle Chronology has recently been fostered by radiocarbon dating of the Anatolian tree ring chronology.[7] Although dendrochronology is a well-established scientific method, doubts about the validity of the statistical techniques employed have been expressed.[8] Therefore some caution in applying tree ring dating to the chronology of the ancient Near East appears justified.

In this paper we analyse the Venus observations of Ammisaduqa using a novel method based on a physical model to compute the visibility of stars and planets in a realistic terrestrial atmosphere. Since the main parameter resulting from this analysis is the atmospheric visual extinction, this method enables us to investigate the magnitude of the atmospheric extinction in Babylon in the 17th century B.C. Our analysis revealed that during a period of about two years the Venus observations appear to be suffering from enhanced extinction. We suggest that this may have been caused by stratospheric aerosols produced in the aftermath of the eruption of the volcano on the Greek island Thera (present day Santorini) in the Aegean Sea. This would provide an interesting link between the chronology of the Aegean Late Bronze Age (1400-1700 B.C.) and that of the ancient Near East (2000-1500 B.C.).

II. The Venus observations of Ammisaduqa reanalysed

Venus is one of the two inner planets in the solar system. Inner planets have orbits around the Sun interior to that of the Earth. As a consequence the elongation of Venus from the Sun never exceeds 47º and Venus may appear on both sides of the Sun as evening and as morning star. Let us consider the course of events starting at inferior conjunction when Venus is situated between the Sun and the Earth. At that point in its orbit it is invisible because of its proximity to the Sun. After as little as one day to a few weeks, while it moves on in its orbit, Venus becomes visible again for the first time near the Eastern horizon just before Sunrise and remains visible for about 10 minutes before disappearing in the increasing brightness of the morning twilight sky. From then on it is visible as morning star for about 8-9 months steadily increasing its elongation from the Sun. After having reached its maximum elongation it starts approaching the Sun again, now at the far side of its orbit as seen from the Earth, until it appears for the last time for about 10 minutes in the Eastern twilight sky when getting close to the Sun again. After remaining invisible for 8-10 weeks during superior conjunction it then reappears but now as evening star in the Western twilight sky just after Sunset. Venus remains visible as evening star for about 8-9 months. It first steadily increases its elongation from the Sun until it reaches its maximum, and then gradually approaches the Sun again until it

[7] Manning et al. 2001
[8] Keenan 2006

disappears in the Western twilight sky. This sequence of four consecutive appearances and disappearances repeats with a period of about 584 days. The Venus tablet may be taken as evidence that these observational facts were known to the Babylonian astronomers in the first half of the 2nd millennium B.C., although not interpreted in terms of a geometric solar system model. A theoretically abstracted version of this kind of knowledge was formulated in the Babylonian astronomical compendium MUL.APIN sometime during the second half of the 2nd millennium B.C.[9]

The Venus observations of Ammisaduqa listed in Tables 1-4 show that after 5 cycles of four consecutive appearances and disappearances the sequence approximately repeats in the Babylonian lunar calendar. This is the well-known Babylonian 8-year Venus period, attested in texts like BM 45728 and BM 41004, dating from the 7th century B.C. and later.[10] From these texts it is clear that the Late Babylonian astronomers were aware of the fact that the Venus phenomena were periodic and that after 8 years the dates of the first and last appearance of Venus receded by about 4 days in the lunar calendar and that after 8 years the longitude of Venus at first and last appearance decreased by about 2.5º in the Babylonian fixed zodiac.

All previous studies of the Venus observations of Ammisaduqa have been based on the use of the well-known concept of the arcus visionis, the distance in degrees between Venus and the Sun measured perpendicular to the horizon on the date of first and last appearance of Venus. At the present day the most comprehensive study of this kind is still the one by Huber et al. (1982). It is based on the authoritative text edition of the Venus tablet by Reiner and Pingree (1975) and it makes use of robust statistical techniques to analyse the data.

In this paper we employ another - more physical - method to analyze the Venus observations. According to this method the visibility of Venus is computed from its brightness in contrast to the brightness of the morning/evening twilight sky using the sensitivity of the human eye. The main free parameter in this model is the value of the visual extinction due to absorption and scattering by molecules and aerosols in the Earth atmosphere. The method has been used before to analyse early Babylonian observations of Saturn, the heliacal rising of Sirius in Egypt and the stellar visibility data in MUL.APIN.[11] A full account of the physics of the visibility model and of the astronomical techniques used in the computation of the positions of the stars and planets in antiquity will be published elsewhere.[12]

The results of our analysis are summarized in Tables 1-4 for the four main chronologies Ammisaduqa 1 = 1702 B.C., 1646 B.C., 1638 B.C. and 1582 B.C. Below we discuss the results for the Long Chronology (Ammsaduqa 1 = 1702 B.C.) in Table 1 in some detail. The results for the other chronologies in Tables 2-4 are computed in the same way and are overall quite similar. This is due to the fact that the four chronologies are separated in time by multiples of the 8-year Venus period (56 or 64 years).[13] Differences between the

[9] Hunger and Pingree 1988, p.73-75; for a recent dating of some of the material in MUL.APIN to the 13th century B.C. see de Jong 2007
[10] Hunger & Pingree 1999, 203-205
[11] de Jong 2002, 2006, 2007
[12] de Jong & Inklaar 2010
[13] Huber et al. 1982, 11-12

Table 1 Venus observations 1702 – 1686 B.C.

Nr.	Omen	Obs	Year	Month	Day	Jul yr	Date	k(ext)	El (º)	h (º)	Δday
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
1	1	EL	1	XI	14	-1700	23-Mar	0.25	5.0	7.3	0
2		MF		XI	18		28-Mar	0.19	3.6	5.9	-1
3	2	ML	2	VIII	10		12-Dec	0.31	4.1	7.7	-4
4		EF		X	19	-1699	17-Feb	0.29	3.6	7.4	2
5	3	EL	3	VI	22		13-Oct	[0.52]	5.6	9.6	[-6]
6		MF		VII	13		4-Nov	0.13	3.8	4.4	-2
7	4	ML	4	IV	1	-1698	15-Jul	0.29	3.1	7.3	-4
8		EF		VI	3		13-Sep	0.18	3.0	5.3	-11
9	5	EL	5	II	1	-1697	4-Jun	<0.10			[4]
10		MF		II	18		22-Jun	>0.70			[7]
11	6	ML		IX	24	-1696	19-Feb	0.19	2.6	5.5	5
12		EF		XI	29		23-Apr	0.25	2.8	6.6	0
13	7	EL	6	VIII	27	-1695	11-Jan	0.24	4.8	6.8	0
14		MF		IX	1		16-Jan	0.29	4.8	7.6	0
15	8	ML	7	V	20		29-Sep	0.28	3.2	7.2	-2
16		EF		VIII	2		7-Dec	0.22	2.5	6.1	-3
17	9	EL	8	IV	24	-1694	22-Aug	<0.10			[18]
18		MF		V	2		31-Aug	>0.70			[8]
19	10	ML		XII	24	-1693	16-Apr	0.25	2.6	6.6	0
20		EF	9								
21	11	EL		XII	10	-1692	20-Mar	0.33	5.3	8.4	-1
22		MF		XII	15		26-Mar	0.22	3.1	6.3	-1
23	12	ML	10	VIII	9		12-Dec	0.28	2.8	7.1	-2
24		EF		X	16	-1691	15-Feb	0.29	3.7	7.4	3
25	13	EL	11	VI	25		18-Oct	0.19	4.2	4.8	2
26		MF		VI_2	8		31-Oct	<0.10			[-3]
27	14	ML	12	I	8	-1690	26-May	[0.64]	6.6	11.9	[-51]
28		EF		VI	25		5-Nov	[0.65]	6.3	11.9	[44]
29	15	EL	13	II	4	-1689	9-Jun	<0.10			[11]
30		MF		II	12		18-Jun	[0.57]	7.6	11.2	[5]
31	16	ML		X	20	-1688	17-Feb	0.19	2.6	5.5	5
32		EF		XI	21		18-Mar	<0.10			[-34]
33	17	EL	14	VII	9		26-Nov	>0.70			[-43]
34		MF		VIII	27	-1687	13-Jan	0.23	4.6	6.7	0
35	18	ML	15	V	19		29-Sep	0.25	2.7	6.6	0
36		EF		VIII	5		11-Dec	0.29	3.7	7.3	3
37	19	EL	16	IV	4	-1686	4-Aug	0.14	3.4	4.0	2
38		MF		IV	20		21-Aug	0.29	6.4	7.8	0
39	20	ML		XII	14	-1685	7-Apr	0.30	3.5	7.5	-6
40		EF		III	25		15-Jul	0.45	4.7	9.6	16

Table 2 Venus observations 1646 – 1630 B.C.

Nr.	Omen	Obs	Year	Month	Day	Jul yr	Date	k(ext)	El (º)	h (º)	Δday
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
1	1	EL	1	XI	14	-1644	5-Mar	0.49	6.6	10.6	-2
2		MF		XI	18		10-Mar	0.17	3.8	5.2	-3
3	2	ML	2	VIII	10		22-Nov	0.38	4.1	8.7	-6
4		EF		X	19	-1643	28-Jan	0.22	2.6	6.2	-4
5	3	EL	3	VI	22		24-Sep	0.47	5.9	9.1	-4
6		MF		VII	13		16-Oct	<0.10			[-4]
7	4	ML	4	IV	1	-1642	27-Jun	0.26	3.4	6.9	2
8		EF		VI	3		26-Aug	0.19	2.6	5.5	-14
9	5	EL	5	II	1	-1641	16-May	0.21	4.3	6.5	1
10		MF		II	18		3-Jun	[0.51]	6.7	10.4	[4]
11	6	ML		IX	24	-1640	1-Feb	0.25	3.0	6.6	2
12		EF		XI	29		3-Apr	0.19	2.4	5.5	-7
13	7	EL	6	VIII	27		24-Dec	0.28	4.6	7.4	0
14		MF		IX	1		29-Dec	0.14	3.5	4.8	-2
15	8	ML	7	V	20	-1639	9-Sep	0.33	3.3	7.9	-3
16		EF		VIII	2		19-Nov	0.20	2.8	5.7	-7
17	9	EL	8	IV	24	-1638	3-Aug	<0.10			[15]
18		MF		V	2		11-Aug	[0.69]	8.2	12.6	[4]
19	10	ML		XII	24	-1637	29-Mar	0.26	2.9	6.8	2
20		EF	9								
21	11	EL		XII	10	-1636	2-Mar	[0.58]	7.7	11.7	[-3]
22		MF		XII	15		8-Mar	0.18	4.1	5.6	-2
23	12	ML	10	VIII	9		22-Nov	0.33	4.3	8.0	-3
24		EF		X	16	-1635	27-Jan	0.24	2.9	6.5	-3
25	13	EL	11	VI	25		29-Sep	0.17	3.6	4.2	3
26		MF		VI_2	8		12-Oct	<0.10			[-5]
27	14	ML	12	I	8	-1634	7-May	[0.59]	5.8	11.3	[-45]
28		EF		VI	25		18-Oct	[0.61]	5.8	11.6	[42]
29	15	EL	13	II	4	-1633	21-May	<0.10			[12]
30		MF		II	12		30-May	0.42	5.5	9.2	3
31	16	ML		X	20	-1632	29-Jan	0.27	2.6	6.9	1
32		EF		XI	21		27-Feb	<0.10			[-40]
33	17	EL	14	VII	9		9-Nov	>0.70			[-42]
34		MF		VIII	27		26-Dec	0.11	3.2	3.7	-3
35	18	ML	15	V	19	-1631	10-Sep	0.27	3.2	7.1	1
36		EF		VIII	5		23-Nov	0.26	3.0	6.8	-2
37	19	EL	16	IV	4	-1630	15-Jul	0.46	6.4	9.9	-2
38		MF		IV	20		1-Aug	<0.10			[-4]
39	20	ML		XII	14	-1629	20-Mar	0.34	3.2	8.0	-5
40		EF		III	25		26-Jun	0.44	5.4	9.6	11

Table 3 Venus observations 1638 – 1622 B.C.

Nr.	Omen	Obs	Year	Month	Day	Jul yr	Date	k(ext)	El (°)	h (°)	Δday
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
1	1	EL	1	XI	14	-1636	6-Mar	0,17	4,1	5,5	1
2		MF		XI	18		11-Mar	0,32	5,0	8,1	1
3	2	ML	2	VIII	10		23-Nov	0,32	3,3	7,8	-3
4		EF		X	19	-1635	30-Jan	0,29	2,9	7,3	1
5	3	EL	3	VI	22		26-Sep	0,27	4,8	6,3	0
6		MF		VII	13		17-Oct	0,26	5,7	7,2	0
7	4	ML	4	IV	1	-1634	29-Jun	0,22	2,7	6,1	6
8		EF		VI	3		28-Aug	0,22	3,1	6,1	-7
9	5	EL	5	II	1	-1633	18-May	<0.10			[5]
10		MF		II	18		5-Jun	>0.70			[9]
11	6	ML		IX	24	-1632	2-Feb	0,21	2,3	5,9	4
12		EF		XI	29		5-Apr	0,25	2,7	6,6	-2
13	7	EL	6	VIII	27		25-Dec	0,10	2,9	3,4	4
14		MF		IX	1		30-Dec	0,41	5,9	9,5	1
15	8	ML	7	V	20	-1631	11-Sep	0,26	3,0	6,8	1
16		EF		VIII	2		20-Nov	0,23	2,6	6,3	-4
17	9	EL	8	IV	24	-1630	4-Aug	<0.10			[18]
18		MF		V	2		13-Aug	>0.70			[8]
19	10	ML		XII	24	-1629	30-Mar	0,24	2,4	6,4	4
20		EF	9								
21	11	EL		XII	10	-1628	4-Mar	0,16	3,7	5,1	2
22		MF		XII	15		10-Mar	0,41	5,3	9,3	2
23	12	ML	10	VIII	9		24-Nov	0,26	3,2	6,9	1
24		EF		X	16	-1627	29-Jan	0,31	3,2	7,6	2
25	13	EL	11	VI	25		30-Sep	<0.10			[7]
26		MF		VI_2	8		13-Oct	0,15	4,1	4,8	-2
27	14	ML	12	I	8	-1626	9-May	[0.55]	5,3	10,8	[-41]
28		EF		VI	25		19-Oct	[0.65]	6,2	12,0	[48]
29	15	EL	13	II	4	-1625	24-May	<0.10			[13]
30		MF		II	12		1-Jun	[0.68]	7,7	12,2	[7]
31	16	ML		X	20	-1624	31-Jan	0,21	2,4	6,0	4
32		EF		XI	21		1-Mar	<0.10			[-34]
33	17	EL	14	VII	9		9-Nov	>0.70			[-40]
34		MF		VIII	27		28-Dec	0,45	6,4	10,0	2
35	18	ML	15	V	19	-1623	12-Sep	0,21	2,9	6,0	4
36		EF		VIII	5		25-Nov	0,31	3,0	7,6	3
37	19	EL	16	IV	4	-1622	17-Jul	0,16	4,6	5,1	2
38		MF		IV	20		3-Aug	0,31	5,9	8,0	0
39	20	ML		XII	14	-1621	21-Mar	0,30	3,5	7,5	-3
40		EF		III	25		27-Jun	0,50	5,4	10,3	15

Table 4 Venus observations 1582 – 1566 B.C.

Nr.	Omen	Obs	Year	Month	Day	Jul yr	Date	k(ext)	El (°)	h (°)	Δday
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
1	1	EL	1	XI	14	-1580	16-Feb	0.47	6.5	10.3	-2
2		MF		XI	18		21-Feb	0.20	3.7	5.9	-1
3	2	ML	2	VIII	10		5-Nov	0.33	4.1	8.0	-4
4		EF		X	19	-1579	11-Jan	0.23	2.8	6.3	-2
5	3	EL	3	VI	22		8-Sep	0.29	5.1	6.6	0
6		MF		VII	13		29-Sep	0.23	2.8	5.9	-1
7	4	ML	4	IV	1	-1578	9-Jun	0.22	2.4	5.9	8
8		EF		VI	3		9-Aug	0.23	2.7	6.3	-5
9	5	EL	5	II	1	-1577	29-Apr	0.13	3.4	4.8	2
10		MF		II	18		17-May	[0.67]	7.4	12.0	[8]
11	6	ML		IX	24	-1576	15-Jan	0.28	2.8	7.1	-1
12		EF		XI	29		18-Mar	0.22	2.2	6.1	-3
13	7	EL	6	VIII	27		6-Dec	0.12	2.6	3.9	3
14		MF		IX	1		11-Dec	0.17	4.3	5.6	-1
15	8	ML	7	V	20	-1575	23-Aug	0.29	3.6	7.1	-2
16		EF		VIII	2		31-Oct	0.21	2.8	5.8	-7
17	9	EL	8	IV	24	-1574	17-Jul	<0.10			[14]
18		MF		V	2		25-Jul	>0.70			[5]
19	10	ML		XII	24	-1573	11-Mar	0.28	3.2	7.2	-2
20		EF	9								
21	11	EL		XII	10	-1572	13-Feb	[0.55]	7.5	11.4	[3]
22		MF		XII	15		19-Feb	0.21	4.0	6.2	1
23	12	ML	10	VIII	9		5-Nov	0.29	3.5	7.4	-2
24		EF		X	16	-1571	9-Jan	0.23	2.8	6.3	-2
25	13	EL	11	VI	25		12-Sep	<0.10			[6]
26		MF		VI_2	8		25-Sep	0.10	2.8	3.4	-2
27	14	ML	12	I	8	-1570	19-Apr	[0.55]	6.0	10.9	[-40]
28		EF		VI	25		1-Oct	[0.66]	6.3	12.0	[51]
29	15	EL	13	II	4	-1569	4-May	<0.10			[9]
30		MF		II	12		12-May	[0.53]	6.7	10.6	[6]
31	16	ML		X	20	-1568	13-Jan	0.28	2.9	7.1	-1
32		EF		XI	21		11-Feb	<0.10			[-37]
33	17	EL	14	VII	9		22-Oct	>0.70			[-38]
34		MF		VIII	27		10-Dec	0.28	5.6	7.7	0
35	18	ML	15	V	19	-1567	23-Aug	0.25	3.1	6.7	1
36		EF		VIII	5		6-Nov	0.28	3.3	7.2	2
37	19	EL	16	IV	4	-1566	28-Jun	0.50	7.0	10.5	-2
38		MF		IV	20		15-Jul	0.12	3.5	4.0	-3
39	20	ML		XII	14	-1565	3-Mar	0.36	3.7	8.4	-8
40		EF		III	25		9-Jun	0.49	5.1	10.2	13

results in Tables 1-4 will be discussed when we compare the quality of fit for the four chronologies.

In Table 1 we list observed and computed data for forty consecutive observations of Venus on tablet 63 of *Enūma Anu Enlil*. Huber et al. (1982) show that the additional twelve observations are mostly untrustworthy. The observed data are taken from the study of Huber et al. and are based on the text edition of Reiner and Pingree (1975). Observations of first appearances and disappearances of all five planets were routinely recorded during the last seven centuries B.C. in the so-called Astronomical Diaries[14], but the Venus observations of Ammisaduqa are the only observations of this kind remaining from the 2nd millennium B.C.

In columns (iv)-(vi) of Table 1 we list the dates of first and last appearance of Venus. The years in column (iv) are those of the reign of king Ammisaduqa. The months in column (v) are represented by Roman numerals (VI_2 is an intercalated second month Ulūlu). The observations are characterized in column (iii) by EL = evening last, MF = morning first, ML = morning last and EF = evening first.[15] Huber et al. (1982) have shown that the date of disappearance (setting) in the text should be taken literally so that the previous day was the date of last appearance. The dates of first appearance in columns (v) and (vi) could therefore be directly taken from Table 4.2 of Huber et al., while the dates of last appearance are adapted by subtracting one lunar day.

The observations in Table 1 form two successive blocks of eight years after which the cycle of first and last appearances roughly repeats (the well-known Babylonian 8-year Venus period). In columns (vii) and (viii) of Table 1 we list the dates in the Julian calendar corresponding to the Babylonian dates for the Long Chronology (Ammisaduqa 1 = 1702 B.C.). Thereto we have made use of attested intercalations derived from independent textual evidence.[16] Lunar dates are computed using modern astronomical ephemerides for the Sun and Moon and a lunar crescent visibility algorithm adapted from Maunder (1911). Lunar dates computed with this algorithm reproduce more than 95% of the dates in the Babylonian calendar during the last six centuries B.C.[17] In any case occasional errors of ± 1 day are immaterial in this analysis. Note that Julian dates change at midnight so that morning observations and evening observations on the same Babylonian date (starting at sunset) differ by one Julian day.

In column (ix) of Table 1 we list the computed values of the visual atmospheric extinction for which Venus becomes visible for the first time or was visible for the last time on the observed date, assuming that the extinction on previous and following days is the same. The computations make use of modern astronomical ephemerides for the Sun, Moon and Venus, the brightness of the twilight sky as a function of the position of the Sun below the horizon and the response function of the human eye. They are carried out for the geographical location of Babylon, the capital of the Old Babylonian empire.

The method has been used before to interpret Babylonian observations of Saturn from Babylon and Uruk in the 7th and 6th century B.C. and to date observations of the first

[14] Hunger & Pingree 1999, p.139-159
[15] This nomenclature was first introduced by van der Waerden (1948)
[16] Reiner & Pingree 1975, Table VI and Huber et al. 1982, Appendix 2
[17] Parker, R.A. & Dubberstein 1956

visibility of stars in the text MUL.APIN to the 13th century B.C.[18] The main free parameter in these calculations is the visual atmospheric extinction. As a side product of these studies the visual extinction in Babylon in the 7th and 13th centuries B.C. could be determined as 0.25 ± 0.05 magnitudes per airmass. An extinction of 0.25 magnitudes per airmass causes a decrease in the transparency of the atmosphere by a factor of 0.79 in zenith, and by 0.037 at an elevation of 4º above the horizon, the height at which Venus appears and disappears under nominal atmospheric conditions.

An extinction value of 0.25 magnitudes per airmass is quite reasonable for the climatic conditions in Babylon. For comparison we may quote mean visual extinction values of 0.13 magnitudes per airmass observed at the European Southern Observatory (desert climate at 2400 m altitude, Chile)[19], of 0.20 magnitudes per airmass at the Wise Observatory (desert climate at 875 m altitude, Israel)[20] and of 0.36 magnitudes per airmass at the Jena University Observatory (continental climate at 356 m altitude, Germany)[21]. Based on the typical shape of the statistical distribution of the extinction at these observatories we expect for an average extinction of 0.25 magnitudes per airmass that 95% of all extinction values fall within the range of 0.10 – 0.50 magnitudes per airmass.

The extinction values listed in column (vii) of Table 1 show that for certain observations no fit could be found for any reasonable value of the atmospheric extinction (k(ext) = 0.10 – 0.70 magnitudes per airmass) and that for others the derived extinction values were improbably large (> 0.50 magnitudes per airmass). These observations are by and large identical to the ones not included in their analysis by Huber et al. (1982) because they were suspected to have been corrupted by scribal errors in the copying process over the many centuries that elapsed between the date of observation in the 17th century B.C. and the date of the oldest extant copies of the text from the 1st millennium B.C. Since observations may also have been missed or delayed by bad weather, some dates may have been "corrected" and/or filled in afterwards by contemporary or later scribes. The possibly corrupted observations in Table 1 are numbers 5, 9, 10, 17, 18, 26-30, 32 and 33. Leaving out these observations we find an average extinction of 0.25 ± 0.07 magnitudes per airmass, exactly equal to the earlier determinations for Babylon in the 7th and 13th centuries B.C.[22]

In the last column of Table 1 we indicate how many days earlier or later the observed date of first or last appearance falls with respect to the nominally expected date (computed for an average extinction of 0.25 magnitudes per airmass). Extinctions larger than the nominal value lead to later first appearances and earlier disappearances, and vice versa. The differences for corrupted dates are quite large and listed in square brackets. Larger differences occur for morning last and evening first observations near superior conjunction of Venus and the Sun, when the relative velocity of Venus with respect to the Sun is small (~ 0.3º per day) so that variations in extinction may lead to large differences in the date of first or last appearance. On the other hand for evening last and morning first observations near inferior conjunction, when the relative velocity of the Venus and the

[18] de Jong 2002, 2007
[19] Burki et al 1995
[20] Vidal et al. 1978
[21] Reimann et al. 1992
[22] de Jong 2002, 2007

Sun is large (~1.5º per day), differences in extinction have only a relatively small effect on the date of first or last appearance. The average of all differences in the dates amounts to 0 ± 5 days (see Table 5).

In column (x) of Table 1 we list the elevation of Venus above the horizon at first or last appearance (including the effect of atmospheric refraction which increases the elevation by 0.1 – 0.2º). In column (xi) we list the values of the (geometric) arcus visionis on the observed dates of first or last appearance. For a low value of the visual extinction of 0.15 magnitudes per airmass the first and last appearances of Venus occur on average at an elevation of ~3º above the horizon when the Sun is ~2º below the horizon, corresponding to an arcus visionis of ~5º. For the nominal value of the extinction of 0.25 magnitudes per airmass these values are about 4º, 3º and 7º, respectively, and when the extinction is enhanced to 0.60 magnitudes per airmass, they increase to about 7º, 5º and 12º. The data in columns (ix) – (xi) further show that the increase of the arcus visionis with extinction is quite well behaved, while the elevation at which Venus first/last appears shows a more erratic dependence on extinction. This latter behaviour is caused by a combination of several subtle effects like the variable brightness of Venus (visual magnitudes varying from -3.6 to -4.5 over its orbit) and the variable geometric situation at the horizon (ecliptic latitude of Venus varying between -8º and +8º, and the inclination of the Venus orbit to the horizon varying between ~45º and ~90º).

The arcus visionis values in Table 1 are very similar to the ones found by Huber et al. (1982) for the 1702 B.C. Venus chronology, differing by at most a few tenths of a degree. Note that only results for first appearance observations can be directly compared because the last appearance dates in Table 1 differ by one lunar day from the disappearance dates of Huber et al.

In our analysis of the data we have assumed that the atmospheric extinction on previous and following days is the same as that on the observed date. This assumption is an idealization of reality because it is well known from astronomical observing practice that the extinction may vary from day to day by as much as 50%.[23] Moreover, the data in Table 1 clearly show that the extinction may vary by factors of up to two between observations.

Smaller extinctions on previous days will lead to earlier dates of first appearance but have no effect on the date of last appearance, while smaller extinctions on following days will lead to later dates of last appearance but do not affect the date of first appearance. A larger extinction on either previous or following days does not affect the observed date. This suggests that the effect of day-to-day extinction variations has only a minor effect on the derived values of the extinction. This is confirmed by the fact that the data in Table 1 do not show any significant asymmetry in the average extinction values determined for the four different synodic phases (EL, MF, ML & EF) separately.

III. A comparison of the different chronologies

In Tables 2-4 we present the results of a similar analysis as in Table 1 but now for the other three chronologies: Ammisaduqa 1 = 1646, 1638 and 1582 B.C., respectively. The results are overall very similar. The main differences are summarized in Table 5.

[23] Rufener 1986

Table 5 Chronology fit parameters

Chronology	Ammsaduqa year 1	Nr of rejected observations		Visual extinction in Babylon	Lunar calendar		
					Day shift	Nisannu 1	Equinox
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
Long	1702 B.C.	12	→ 9	0.25 ± 0.07	0 ± 5	7-May	5-Apr
high Middle	1646 B.C.	12	→ 10	0.28 ± 0.11	-2 ± 5	18-Apr	5-Apr
low Middle	1638 B.C.	11	→ 8	0.27 ± 0.09	1 ± 4	19-Apr	4-Apr
Short	1582 B.C.	11	→ 8	0.26 ± 0.10	-1 ± 4	31-Mar	4-Apr

The number of observations rejected because they require improbable or impossibly small or large values of the visual atmospheric extinction in column (iii) of Table 5 are quite similar for all four chronologies. Observation nrs. 10, 17, 18, 27, 28, 29, 32 and 33 were discarded as corrupted for all four chronologies. These happen to be exactly those that were characterized as “bad” by Huber et al (1982). For the Low Middle Chronology and the Short Chronology one observation less is discarded.

The average visual extinction values listed in column (v) of Table 5 for the four chronologies are identical within their standard deviations. If the magnitude of the standard deviation, interpreted as a measure of the observational spread in the extinction values, may be taken as a criterion for quality of fit, the data in column (v) of Table 5 would favour the Long Chronology.

Note that, contrary to what was found in Table 1, there are a few values of the arcus visionis in Tables 2-4 that differ by about 1 to 2 degrees with those of Huber et al. (1982), for instance for observation nr. 14 in Tables 2 and 3. This is caused by the slightly different lunar crescent visibility algorithm used in our model which may occasionally lead to a difference of one day in the transformation of the Babylonian lunar calendar to the Julian calendar.

In column (vi) of Table 5 we list the average shift in the lunar day count computed from the numbers of days in columns (xii) of Tables 1-4 that the observations were later or earlier than expected for a nominal atmosphere. This shift characterizes how well the sequence of first and last appearance dates is lined up with the lunar calendar. While no firm conclusions can be drawn from these numbers because the uncertainties (standard deviations) exceed the magnitude of the average shift, the Long Chronology seems to provide the best fit to the lunar calendar and the High Middle Chronology the worst.

In Old Babylonian times the pattern of intercalation of lunar months was governed by the intention to keep the lunar calendar lined up to the agricultural year, characterized by the date harvest in the fall and the barley harvest in the spring. Fotheringham has shown that on average the date harvest fell in Ulūlu (month VI) and the barley harvest in Addaru (month XII).[24] This is consistent with the tabulated lengths of daylight and of nighttime for the 15th and 30th day of each month of the ideal Old Babylonian calendar on Tablet 14 of *Enūma Anu Enlil*.[25] There we find that the equinox (length of day = length of night) fell on Addaru 15 so that on average the beginning of the Old Babylonian year (Nisannu 1) fell about 15 days after Spring Equinox. Occasionally the Old Babylonian calendar

[24] Fotheringham in Langdon et al. (1928), 69-75
[25] Hunger and Pingree (1999), 47-50

could be quite a bit out of step with the agricultural year. During Hammurabi’s reign the beginning of the year at one time moved forward by about 2.5 months due to 4 intercalations in 4 consecutive years, and during the reign of Ammisaduqa the beginning of the year at one time slipped backwards by about 7 weeks in 5 consecutive years without being corrected by intercalation.[26]

In columns (vii) and (viii) of Table 5 we list the median date of the first day of the Babylonian calendar (Nisannu 1) and the date of the Spring Equinox during the first sixteen years of the reign of Ammisaduqa according to the four different Venus chronologies. These data show that for the Long Chronology the Babylonian calendar is on average more than two weeks late, and for the Short Chronology almost three weeks early, while for the two Middle Chronologies the calendar (averaged over sixteen years) seems to agree nicely with Old Babylonian calendar practice.

Although for each of the criteria in Table 5 a preference for one or at most two of the chronologies might be expressed, our analysis of the Venus observations does not allow us to choose between the four Venus chronologies. Therefore, it seems that we are still at the stage first quite clearly formulated by Neugebauer (1941) that additional independent historical evidence is required to choose between the different possible Venus chronologies.

Two studies presenting such independent evidence, although with contradictory results, have been published. One study, by Huber et al. (1982), uses a list of textually attested Old Babylonian month lengths to demonstrate that the Long Chronology is by far to be preferred. The other study by Manning et al. (2001) shows that radiocarbon dating of tree rings in Anatolian archeological monuments supports the (Low) Middle Chronology. A third suggestion by Gurzadyan, published as part of a general reappraisal of the archeological evidence[27], was convincingly shown by Huber (2000) to be invalid.

IV. Effects of the Santorini eruption on the Venus observations

The fact that our method of computing the visibility parameters of Venus is based on the physics of the Earth atmosphere allows us to investigate whether some of the large extinction values found in the analysis may be attributed to physical causes rather than to scribal errors. One well-known cause for variations in the atmospheric extinction is the aerosol loading of the stratosphere in the aftermath of volcano eruptions.[28] This raises the interesting question whether traces of the notorious Minoan eruption of the volcano on the Greek island Thera (present-day Santorini) in the Aegean Sea may be identified in the Venus observations of Ammisaduqa.

The Santorini eruption caused an environmental catastrophe in the Eastern Mediterranean[29] and its consequences may have inspired several Greek myths, among them Plato’s story of Atlantis (as described in the Timaeus and Critias). Since the Santorini eruption has recently been dated by radiocarbon tree ring dating to 1627-1600

[26] Huber et al. 1982, p.8
[27] Gasche et al. 1998
[28] Rampino et al. 1988
[29] Bruins et al. 2008

B.C.[30] a connection between the two might provide an anchor point for the Venus chronology.

In view of the evidence that the Santorini eruption caused climatic changes affecting tree growth throughout the Northern hemisphere for an episode of several years[31], observable effects in relatively nearby Mesopotamia seem probable. It is known from other catastrophic volcano eruptions in historic times that the Earth atmosphere is strongly disturbed for several years afterwards. Notorious examples are the eruptions of the Tambora (1815) and Krakatau (1883) volcanoes in Indonesia.

Because the Low Middle Chronology (Ammisaduqa 1 = 1638 B.C.) is the only one for which the Venus dates have some overlap with the radiocarbon time window of the eruption (1627-1600 B.C.) we start out by adopting this chronology for our analysis below. Among the data for this chronology in Table 3 are three observations (nr. 27, 28 and 30) with improbable but not impossibly large extinction values (0.50-0.70 magnitudes per airmass). These observations were discarded by Huber et al. (1982) because they were extremely advanced or delayed in time compared to the nominally expected date. As indicated in column (xii) of Table 3 the morning last and evening first observations of Venus in 1627 B.C. are 41 days early and 48 days late, respectively. Also the morning first observation of Venus in June 1626 B.C. is exceptionally late. We propose that the enhanced extinction values in 1627 and 1626 B.C. may be caused by the aerosol loading of the stratosphere due to the eruption of the volcano on Santorini. The enhancement is statistically significant because it exceeds the 3-σ margin of the average extinction. Furthermore, it lasts for 1 to 2 years which is about the half-life of aerosols produced by a volcano eruption in the stratosphere.

To investigate the strength of the Santorini eruption we show in Fig. 1 a plot of the excess zenith optical depth due to stratospheric aerosols as a function of time from 1 January 1628 B.C. to 1 January 1623 B.C. The data points are derived from the extinction values in Table 3 by first subtracting the average nominal atmospheric visual extinction of 0.27 +0.23/-0.17 magnitudes per airmass (covering the full range of observed extinction values in the Babylonian atmosphere) and then multiplying by 0.921 to convert magnitudes to optical depths.[32] The curves are scaled versions of the one derived by Stothers (1984) for the Tambora eruption. The three curves shown are for three different eruption dates: 1 November 1628 B.C., 1 February and 1 May 1627 B.C., respectively. They have been scaled so as to fit the data points within the error bars. The two shaded curves represent the two extreme cases which are constrained by the last unaffected Venus observation on 13 October 1628 B.C. and the first affected observation on 9 May 1627 B.C. The solid curve represents the intermediate case with an eruption date of 1 February 1627 B.C. Thus the Venus data suggest that the volcano on Santorini erupted sometime after 13 October 1628 B.C. and before 1 May 1627 B.C.

From the data in Fig. 1 we find that the maximum excess optical depth due to the Santorini eruption amounts to 0.3 ± 0.1 and that the timescale of stratospheric cleaning is of the order of several years. From a comparison with optical depth data of recent historic volcano eruptions we estimate that the amount of aerosols injected into the atmosphere by the Santorini eruption was about 1.5 times larger than that ejected by Krakatau in 1883,

[30] Friedrich et al. 2006
[31] Grudd et al. 2000
[32] Stothers 2001, eq. (1)

and that the corresponding excess mass of stratospheric aerosols amounted to ~45 Megatons.[33]

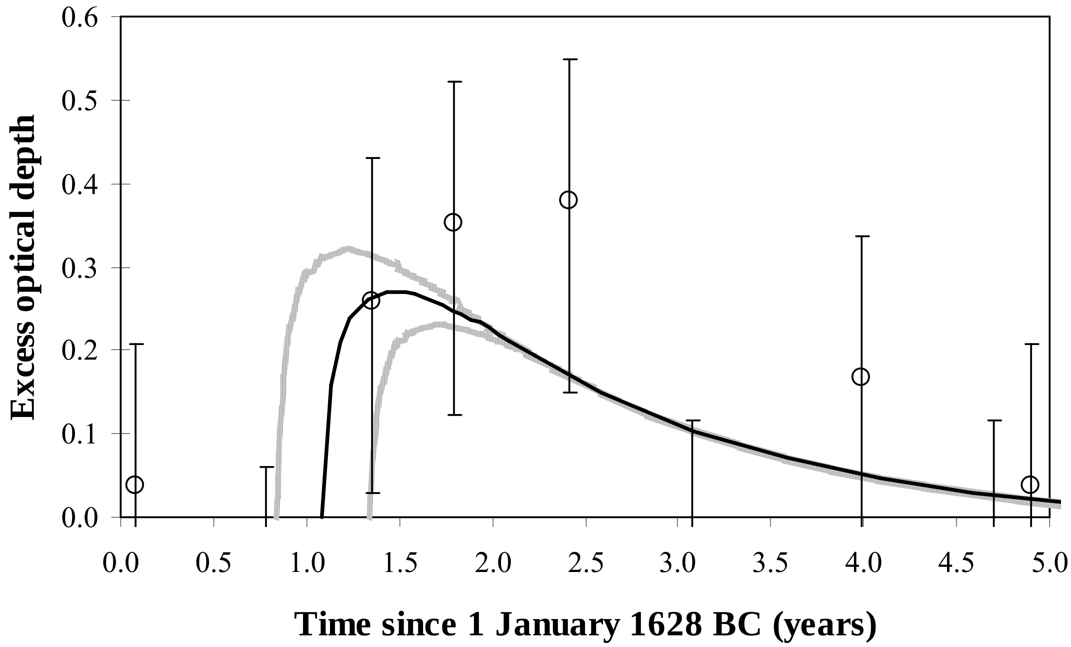

Figure 1 Excess visual optical depth in the atmosphere of Babylon due to the Santorini eruption as a function of time. The data points are derived from the extinction data in Table 3 for the Low Middle Chronology (see text). The curves are scaled versions of the one derived for the Tambora eruption. The shaded curves represent limiting cases with eruption dates of 1 November 1628 B.C. (left) and 1 May 1627 B.C. (right). The solid curve represents the intermediate case with an eruption date of 1 February 1627 B.C.

In our visibility model we have assumed that the brightness distribution of the twilight sky is a function of the solar depression below the horizon. While this is probably a fair assumption for a normal atmosphere, there are reports from the aftermath of the Krakatau eruption which suggest that stratospheric aerosols may have affected the sky brightness during twilight.[34] This effect is difficult to model and therefore renders the exact values of the enhanced extinction and the derived aerosol loading somewhat uncertain.

The apodoses (forecasts) in the omina associated with observations 27 through 30 in the text of the Venus tablet[35] do not reflect ominous events like failed crops or other signs of a “volcanic winter”. This might have been expected if the apodoses were based on events contemporaneous with the observations. However, since the method by which the omina are composed and associated with the observations is unknown, the absence of a reference to possible consequences of the eruption cannot be taken as an argument against the validity of our proposal.

[33] Stothers 2001, eq. (5)
[34] Simkin & Fiske 1983, p.154
[35] Reiner and Pingree 1975

V. Discussion

By interpreting the large extinction values in Tables 1-4 for the Venus observations in the 12th and 13th year of king Ammisaduqa in terms of a physical process we reduce the number of observations in Tables 1-4 that must be discarded to 8 or 9 (see column (iv) of Table 5), less than 25% of the total number. The fact that they cluster in a time span of about two years, the typical cleaning time of the stratosphere (see Fig. 1), may be considered a strong point in favour of our hypothesis. Accepting these observations as valid rather than discarding them as corrupted may be taken as an example of the philological principle: "Lectio difficilior potior"

Our dating of the Venus observations heavily rests on the narrow time window 1627-1600 B.C. (at 95% confidence level) that we adopted for the Santorini eruption. This time window is based on radiocarbon dating of a tree ring sequence in an olive branch found among the ruins of the ancient city of Akrotiri that was buried by the eruption.[36] If we would have chosen the more generous time window of 1683-1611 B.C. (at 95% confidence level) based on radiocarbon dating of a number of samples of organic materials also found in Akrotiri[37], the high Middle Chronology (Ammisaduqa 1 = 1646 B.C.) would also have been allowed.

Recently doubts have been expressed on the reliability of the Anatolian radiocarbon tree ring dating.[38] If this critique is indeed to be taken serious, it is conceivable that the chronological window of the Santorini eruption is sufficiently widened that it would comprise all four Venus chronologies. In that case, the argument can be turned around: the Venus observations may be used to date the Santorini eruption. In fact this may well be the case because the Old Babylonian month lengths test, which strongly supports the Long Chronology, seems statistically much more robust than the wiggle-matching of radiocarbon dated tree ring sequences.

Adopting this point of view we find from the data in Table 1 that the Santorini eruption would have occurred somewhere between 1 November 1692 B.C. and 1 May 1691 B.C. Note that this is only 9-8 years further back in time than allowed by the upper limit of the radiocarbon time window quoted above. The physical parameters characterizing an eruption in 1692/1691 B.C. are quite similar to those derived from the data in Fig. 1 for an eruption in 1628/1627 B.C.

VI. Conclusions

In this article we have shown that the results of an analysis of the Venus observations on Tablet 63 of *Enūma Anu Enlil* in terms of a physical model of the visibility of Venus in a realistic twilight atmosphere do not allow a decisive choice between the four different Venus chronologies. On the other hand the results do enable us to suggest that the enhanced atmospheric extinction affecting the Venus observations in the 12th and 13th year of the reign of the Babylonian king Ammisaduqa may be attributed to the historic

[36] Friedrich et al. 2006
[37] Manning et al. 2006
[38] Keenan 2006

volcano eruption on the Greek island Thera (Santorini). Accepting this hypothesis, we show that the eruption either occurred in 1628/1627 B.C. (if the radiocarbon tree ring dating window of the eruption is accepted), or in 1692/1691 B.C. (if the Long Chronology of the ancient Near East is accepted). An eruption of the Santorini volcano in 1628/1627 B.C. implies that the Low Middle Chronology of the ancient Near East would be the correct one. The fact that the Venus observations show traces of the Santorini eruption contributes to establishing their historicity.

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