The Earliest Candidates of Auroral Observations in Assyrian Astrological Reports: Insights on Solar Activity around 660 BCE

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Abstract

Auroral records found in historical archives and cosmogenic isotopes found in natural archives have served as sound proxies of coronal mass ejections and solar energetic particles (SEPs), respectively, for dates prior to the onset of telescopic sunspot observations in 1610. These space weather events constitute a significant threat to a modern civilization, because of its increasing dependency on an electronic infrastructure. Recent studies have identified multiple extreme space weather events derived from SEPs in natural archives, such as the event in 660 BCE. While the level of solar activity around 660 BCE is of great interest, this had not been within the coverage of the hitherto-known datable auroral records in historical documents that extend back to the 6th century BCE. Therefore, we have examined Assyrian astrological reports in the 8th and 7th centuries BCE, identified three observational reports of candidate aurorae, and dated these reports to approximately 680 BCE–650 BCE. The Assyrian cuneiform tablets let us extend the history of auroral records and solar activity by a century. These cuneiform reports are considered to be the earliest datable records of candidate aurorae and they support the concept of enhanced solar activity suggested by the cosmogenic isotopes from natural archives.

Unified Astronomy Thesaurus concepts: Solar-terrestrial interactions (1473); History of astronomy (1868); Solar coronal mass ejections (310); Solar activity (1475); Geomagnetic fields (646)

1. Introduction

The Sun causes infrequent but high-impact space weather hazards. These space weather events represent a significant threat to modern society, as it becomes increasingly dependent on a technology-based infrastructure and is therefore very vulnerable to such hazards (Daglis 2001; Dyer et al. 2018; Riley et al. 2018). These space weather hazards are caused by coronal mass ejections (CMEs) and solar energetic particles (SEPs) from our Sun (Daglis 2001; Vaquero & Vázquez 2009; Dyer et al. 2018; Riley et al. 2018), although their intensity correlation is at best moderate (Gopalswamy et al. 2012).

Recent analyses of $^{14}$C in tree rings have revealed anomalous enhancements in 774/775 CE and in 992/993 CE or 993/994 CE (Miyake et al. 2012, 2013; Usoskin et al. 2013; Büntgen et al. 2018) and these enhancements have been associated with anomalous SEP events, on the basis of simultaneous enhancements of $^{14}$C in other tree rings and enhancements of $^{10}$Be and $^{36}$Cl in polar ice cores (Mekhalfi et al. 2015; Büntgen et al. 2018). These events occurred far before the onset of instrumental observations, well outside the more modern range of wide observational coverage (see Vaquero & Vázquez 2009; Clette et al. 2014). Therefore, in order to infer the general trend of solar activity and the occurrence of CMEs, candidate auroral records have been sought in historical documents around these events (e.g., Usoskin et al. 2013).

Further analyses in the cosmogenic isotope data have identified a third extreme SEP event in 660 BCE (Park et al. 2017; O’Hare et al. 2019). This event occurred slightly before the established coverage of datable records of candidate aurorae back to the 6th century BCE (Stephenson et al. 2004; Silverman 2006; Hayakawa et al. 2016; see Appendix A).

However, the Babylonians and Assyrians had started astronomical observations7 at the latest in the 8th century BCE (Steele 2012). Already in the 7th century BCE, Assyrian kings had collected and received astrological reports from professional astrologers, to interpret the ominous meaning of observed celestial events (Hunger 1992). Therefore, in this study, we survey candidate auroral records in Assyrian astrological reports and compare them with the available scientific data, in order to extend our knowledge on variable solar activity and the occurrence of CMEs back into the 7th century BCE.

2. Materials and Methods

Most of the extant reports were written during the 8th and 7th centuries BCE and were collected in the royal archives of Nineveh, the last capital of the Assyrian Empire after the reign of Sennacherib (r. 705 BCE–681 BCE). These reports were comprehensively collected and edited in Hunger (1992). Assyrian kings employed scholars that specialized in divination. These scholars sent reports on celestial phenomena to their employer-kings. These reports describe the astrological interpretations of these phenomena. The interpretations are often accompanied by technical phrases in the Enûma Anû Enlil (EAE) and other omen collections. Most of the reports

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7 Here, we use the terms of astronomy and astrology in the Assyrian epoch, based on their purpose: astronomy for calendar-setting and prediction of celestial phenomena and astrology for divinatory prediction of terrestrial events from immediate celestial phenomena.
were written on palm-sized rectangular tablets, and the texts are inscribed along the longer sides of the tablets (Hunger 1992).

Hunger (1992) explains that reports of such ominous celestial events may involve the following six elements.

I. Quotations of given omens from EAE
II. Explanations of those omens
III. Statements of celestial observations, occasionally including predictions
IV. Letter-like messages
V. Sender’s name
VI. Date

The first element is involved in almost all the extant astronomical reports and cited from EAE, on the basis of what they observed. According to Hunger (1992, p. xvi), “In principle, no other information is required, since the protasis of a celestial omen always implies an observation. There would seem to be no need to explicitly repeat what was observed.” Occasionally, actual observations are recorded, and the reported ones are often different from the quoted omen protases (sentences with cited omens). Especially when the real celestial events seemed not to repeat the protases clearly, explanations and statements of observations would have been necessary. On the contrary, observational statements were not necessary when protases of celestial omens implied observed events (Hunger 1992). In the report no. 288 edited by Hunger (1992), Nabû-qišša reports the observation of conjunction of Jupiter and Mars only by quoting some omen protases concerning this kind of conjunction and calls for a ritual against this bad omen. Therefore, unless otherwise endorsed, it is surmised that quoted protases indicate actual celestial events with a fair degree of precision.

Although the datable astronomical reports range chronologically from 709 BCE to 649 BCE (Brown 2000), we have only one from the 8th century BCE (no. 501; Hunger 1992). The earliest known Babylonian astronomical diary is dated in the same period (~651 BCE; Sachs & Hunger 1988; Hayakawa et al. 2016). We found 14 Assyrian and 30 Babylonian scholars as senders of the reports (Hunger 1992). Note that Babylonia was under the rule of the Assyrian Empire in this epoch (until 626 BCE). Scholars had made regular observations and reported their observational results to the Assyrian kings. Two reports (Hunger 1992, nos. 7 and 79) clearly show this kind of activity by the scholars. In the first report, Issār-šumu-ēreš reported the observations for Mars twice or thrice in one day. It had set and could not be seen. Issār-šumu-ēreš anticipated the king’s inquiry as to its ominous meaning and wrote his answer to negate the existence of such a sign in the report. In the second report, Nabû-ahê-eriba reported a continuous observation for the Moon on the 29th day of a certain month and probably on the next day. These accounts show that the astronomical reports are based on the regular observations, as stated by Hunger (1992).

Scholars sent their reports from Assyria, the area around Nineveh (N36°21’ E43°09’), and from cities in Babylonia such as Babylon (N32°33’, E44°26’), Borsippa (N32°24’, E44°20’), Cutha (N32°46’, E44°20’), Dilbat (N32°10’, E44°28’), Ur (N30°58’, E46°06’), and Uruk (N31°20’, E45°38’) (Brown 2000).

### Table 1

| ID  | Tablet | Date Range | Observer | Site | Figure |
|-----|--------|------------|----------|------|--------|
| R1  | Rm211  | 679 BCE–655 BCE | Issār-šumu-ēreš | Nineveh | I(a) |
| R2  | K748   | 677 BCE–666 BCE | Nabû-ahê-eriba | Nineveh | I(b) |
| R3  | 80-7-19-19 | 679 BCE–670 BCE | Zakiru | Babylon | N/A |

Scholars quoted the protases and stated the observations about unusual astronomical phenomena such as comets (šallummu), meteors (kakkabu rabû), and halos (tarbašu) (Hunger 1992). These reports show the Assyrian scholars’ rich technical terms and deep knowledge of various celestial events.

Unfortunately, only a small fraction of extant reports were dated explicitly. However, as these reports were drafted at the time of occurrence of given celestial events, these events must have occurred during the tenure of the astrologers mentioned in the reports. Therefore, we can constrain their date ranges based on when the relevant astrologers were actively working under the Assyrian court.

### 3. Results

In order to survey candidate auroral reports around the 7th century BCE, we have consulted the astrological reports in Hunger’s critical edition (Hunger 1992) and noted all mentions of reddish luminous phenomena in the sky (see, Stephenson et al. 2004; Hayakawa et al. 2016). Among the 389 astrological reports surveyed, we have found three containing auroral candidates: “red glow” (R1 = Rm211), “red cloud” (R2 = K748), and “red sky” (R3 = 80-7-19-19) (Appendix B). These three auroral candidates are significantly rare within the surviving astrological reports (~0.8%), whose main focus was lunar and planetary phenomena (Hunger 1992). These events are therefore considered sufficiently notable for the Assyrians and Babylonians to include them in astronomical discussions. Table 1 provides their estimated date ranges, references, and tablet names in Table 1. After identifying these reports, we have examined the available original cuneiform tablets in the British Museum and made copies (Figure 1), transliterated the original texts, and translated them into English (see Appendix B).

### 4. Dates and Descriptions of These Astrological Reports

Tablet R1 (tablet Rm211) involves the technical term, akukat “red glow.” This term is also found in the known candidate auroral report for 567 BCE March 12/13 (Stephenson et al. 2004; Hayakawa et al. 2016; see Appendix A). This astrological report describes a blaze of this red glow in the month of Sivan (III) along with its associated omen interpretation. There are cases of a red glow blazing at the zenith, during motion from south to north, being associated with a south wind. This is consistent with the auroral report at Barnstaple in 1872, when the aurora extended from the south to the zenith (Hall 1872; see Appendix C). Hunger (1992) has identified the tablet R1 (tablet Rm211) as one of the astrological reports of the scholar...
Issar-šumu-ēreš to the Assyrian kings Esarhaddon and Assurbanipal. We estimate the R1 date range as falling between 679 BCE and 655 BCE, according to the dates when Issar-šumu-ēreš was working in the Assyrian court (Hunger 1992; Parpola 1993; Pearce 2000).

Tablet R2 (tablet K748) contains the term “red cloud.” Aurorae were certainly described using the term “red cloud” even in the 19th century, as in the case of the 1859 August storm (Loomis 1860; see Appendix C). Tablet R2 is one of the astrological reports from Nabû-ahḫē-eriba to the Assyrian kings Esarhaddon and Assurbanipal. As Nabû-ahḫē-eriba worked under the Assyrian court between 677 BCE and 666 BCE (Hunger 1992; Parpola 1993), the date range of the tablet K748 is estimated accordingly.

Tablet R3 (tablet 80-7-19,19) reports “red covers the sky.” It is known that auroral displays were reported to have covered the entire sky during extreme space weather events (e.g., Loomis 1860; Hall 1872; see Appendix C). Tablet R3 is one of astrological reports from Zakiru, who was probably active in Babylon between c.a. 679 BCE and 670 BCE (Hunger 1992; Groß, 2011). Therefore, its date range is defined accordingly.

5. Scales of Associated Magnetic Storms

Zakiru was a Babylonian scholar, and Issar-šumu-ēreš and Nabû-ahḫē-eriba were Assyrian scholars active at Nineveh, as summarized in Table 1. Although not very frequent, aurorae had certainly been visible in the Middle East during extreme magnetic storms. In particular, during the extreme storms in 1870 October, aurorae were reported at Cairo and Baghdad (Silverman 2006; Vaquero et al. 2008); during the extreme storms in 1872 February, aurorae were reported at Alexandria and Cairo, respectively (Silverman 2008).

Moreover, the Middle East was closer to the north geomagnetic pole in the Assyrian epoch. While the north geomagnetic pole is situated near the region of North America today, it was situated in the region of Eurasia in the mid- to early 7th century BCE due to the secular variation of the geomagnetic field (Korte & Constable 2011). Figure 2 shows the secular variation of magnetic latitudes (MLATs) for Babylonian and Assyrian cities represented by Nineveh (N36°21′, E043°09′), Babylon (N32°33′, E044°26′), and Ur (N30°58′, E046°06′). Their MLATs during the Assyrian and...
Babylonian period were $\approx 8^\circ$ further poleward compared with their MLATs in the 1870s. Therefore, ancient aurorae would have been visible much more frequently in Mesopotamia during large magnetic storms than in the 1870s, when aurorae were indeed observed in the Middle East (Silverman 2006, 2008; Vaquero et al. 2008).

Indeed, the MLATs of Assyrian and Babylonian cities in the 7th century BCE ranged from $35^\circ$ to $41^\circ$, which is further poleward (magnetically) than Hokkaido (Japan) at recent times, where reddish aurorae are often observed during small and moderate magnetic storms (Shiokawa et al. 2005). These recent Japanese auroral observations at mid to low MLATs usually indicate auroral luminosity near the horizon in the poleward direction. However, overhead aurorae in Hokkaido have been reported for great magnetic storms like the 1909 one (Hayakawa et al. 2019). Therefore, the occurrence of aurorae over Assyrian and Babylonian cities in the interval 679 BCE–655 BCE let us reasonably suppose that large interplanetary CME and subsequent strong magnetic storms occurred in this same interval.

These astrophysical reports describe reddish luminous phenomena in the sky: “red glow,” “red cloud,” and “red sky.” The reddish color is quite typical of low-latitude aurorae and stable auroral red (SAR) arcs with O I emission (630.0 nm). The former one, reddish aura, is caused by low-energy electrons ($\lesssim 100$ eV) and is frequently accompanied by greenish emissions (557.7 nm; Rees & Roble 1975). The latter one, the SAR arc, appears during the main phase and recovery phase of magnetic storms, equatorward of the auroral oval, and extends further in the longitudinal directions for a few hours (Kozyra et al. 1997) or even longer (Craven et al. 1982). They are caused by downward heat flux ($\approx 3000$ K) or precipitation of low-energy particles (Kozyra et al. 1997). Although they are generally not bright, some bright SAR arcs have been reported ($\approx 13$ kilo Rayleigh) during large magnetic storms (Baumgardner et al. 2007). The SAR arcs can be distinguished from the reddish aura by comparing with greenish emissions (557.7 nm; Miyaoka et al. 1990; Shiokawa et al. 2005). However, it is, in general, difficult to distinguish them without spectroscopic instruments.

6. Chronology in Longer-term Solar Variability

Figure 3 shows a comparison of $^{14}$C concentrations in tree rings (Reimer et al. 2013; Park et al. 2017) and the date ranges of the three candidate auroral records: 679 BCE–655 BCE (R1), 677 BCE–666 BCE (R2), and 679 BCE–670 BCE (R3). Although an extremely large SEP event causes a detectable $^{14}$C increase, as seen in the 777/775 CE event, a normal $^{14}$C variation is caused by a modulation of galactic cosmic rays, due to changes in the interplanetary magnetic field (Beer et al. 2012). The large $^{14}$C excursion from 810 BCE to 720 BCE corresponds a period of extremely low solar activity, called a grand solar minimum (Usoskin et al. 2007).

After this grand solar minimum, $^{14}$C concentrations decrease as solar activity recovers, and then a rapid $^{14}$C increase is observed in $\approx 660$ BCE. From multiproxy analyses of $^{14}$C in tree rings and $^{10}$Be and $^{36}$Cl in ice cores, the origin of this rapid $^{14}$C increase is considered to be one or the more extreme SEP event(s) that occurred during the period of increasing solar activity (O’Hare et al. 2019). Two of these records (R2 and R3) fall in this period and hence may be associated with this enhanced solar activity. R1 has a rather broad time range (679 BCE–655 BCE) and covers both the enhanced solar activity during 680 BCE–670 BCE and the anomalous enhancements of cosmogenic isotopes around 660 BCE. Although R1’s exact date is an open question, these reports seem to provide snapshots of enhanced solar activity during 680 BCE–670 BCE and possibly the period around the 660 BCE event (Park et al. 2017; O’Hare et al. 2019).

7. Conclusion

In this study, we have surveyed the Assyrian astrological reports for the 7th century BCE. We have identified three candidate auroral observations in the Assyrian astrological reports and identified their probable date ranges: 679 BCE–655 BCE (R1: Rm211), 677 BCE–666 BCE (R2: K748), and 679 BCE–670 BCE (R3: 80–71, 19, 19). Although we cannot further refine the date ranges at this stage, these Assyrian reports...
provide snapshots of solar activity in the early 7th century BCE around extreme SEP events (Park et al. 2017; O’Hare et al. 2019) and allow us to trace the history of solar activity back a century earlier than the earliest existing datable auroral reports in the 6th century BCE (Stephenson et al. 2004; Silverman 2006; Vaquero & Vázquez 2009; Hayakawa et al. 2016).

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Author Contributions

H.H. prepared the manuscript and coordinated the discussions, Y.M. analyzed the cuneiform tablets, Y.E. detailed the auroral science, and F.M. analyzed the contemporary cosmogenic isotopes. All the authors read this manuscript and contributed to the discussions.

Appendix A
Existing Earliest Auroral Records

The earliest datable auroral record has been considered to be the Babylonian record on 567 BCE March 12/13 (VAT 4956; Stephenson et al. 2004; Hayakawa et al. 2016, Appendix Figure 4). An astronomer–astrologer (tupšar EAE) reported this event as (see also Stephenson et al. 2004; Hayakawa et al. 2016):

Transliteration: GE₆ 29 a·ku₆·ku₉·{ku₆·}tu₄
ina·ŠU KUR 2 DA[NNA ....]

Translation: Night of the 29th, red glow flared up in the west: 2 double[-hours ....].

Its cuneiform text is shown in Figure 4. The MLAT of Nippur is computed to have been ≈36°2 at that time with CALS3k4b.

Appendix B
Transliteration and Translation of Assyrian Astrological Reports for the Candidate Auroral Records

We examined the available original cuneiform tablets in the British Museum for each of the three candidate auroral records and created trace copies as the basis for transliterations and translations. Because tablet 80-7-19,19 for the report of a “red sky” could not be delivered when we requested an examination, we made transcriptions and translations, relying upon existing copies by Pinches (1882, p. 10) and Harper (1896, p. 439), as well as the transliteration of Hunger (1992, p. 173).

As shown in Section 2, two accounts show that the astrological reports are based on the regular observations and drafted with astrological interpretations upon the occurrence of cited celestial events. Unless otherwise endorsed, it is surmised that quoted protases in the reports indicate observed celestial events.

Tablet R1: Rm211 (Preserved in the British Museum, RMA 275; Hunger 1992, no. 35). Copy of 1–6 and r.1 (Figure 1(a)).

Tablet R1 (Rm211; Figure 1(a)) is one of the astrological reports of the scholar Ištār-Sumu-ēreš to Assyrian kings Esarhaddon and Assurbanipal (collected by Hunger 1992, pp. 4–21). The following transliteration and restoration are based on the photos of the tablets © Hisashi Hayakawa (taken courtesy of the Trustees of the British Museum) and the transliteration and restoration of Hunger (1992, p. 19). Hunger’s restoration, except for the name of the sender, was proposed by Neugebauer & Weidner (1915, pp. 56–61) on the
basis of three astrological omens in the tablet VAT 9417. Its
text was edited there, but the tablet number was later shown by
Weidner (1941, p. 175).

Translation
1 1 ina 1-6SIG4,1 a-[u-ka-tum MÛ-ûh]
2 MUNUS.KUR ina [KUR GÄL-ši]
3 1 a-ku-‘ka-tum [M.U14.LU rak-bat]
4 UD-mu [ŠU-ăn]
5 1 a-ku-ku-tum ina [AN.PA it-ta-na-an-pab]
6 KUR [i-ni-neš-ši KLIN.M.TUR-ār]
r.1 ša LU.[1941, p. 175]

Note.
Akkadian umu (UD-mu) means not only daytime but also day as a unit of
time (from one sunset to the next sunset) (Roth 2010, pp. 138–155). Therefore,
we cannot narrow down its time range to just daytime (daylight).

Tablet R2: K748 (Preserved in the British Museum, RMA 248; Hunger 1992, no. 78). Copy of 1–2 and r.1 (Figure 1(b)).

The translation is based on the photos of the tablets ©
Hisashi Hayakawa (taken courtesy of the Trustees of the
British Museum) and the transliteration of Hunger (1992, p.
45). The sign group sa-a-mu in 1.1 is an erroneous Akkadian
syllabic script for the Sumerogram SA₅. It should be read
sämtu because erpetu (IM.DIRI) is not a masculine noun but
rather a feminine noun. The sign groups it-ta-na-dāš-kan and ša-
a-ru on 1.2 are Akkadian syllabic script for GAR.GAR-mu and
TU₁₅.

Translation
1 1 IM.DIRI | SA₅ ina AN-e
2 GAR.GAR-mu TU₁₅ ZI-a
3 it-ta-na-dāš-kan ša-a-ru

blank
r.1 ša“PA—PAB.MEŠ—SU

Translation
1 If a red cloud keeps being placed in the sky,
2 a wind will rise.

r.1 From Nabû-ahhê-
eriba.

Tablet R3: 80-7-19,19 (Preserved in the British Museum,
RMA 267A; Hunger 1992, no. 309)
The transliteration is based on copies (Pinches 1882, p. 10;
Harper 1896, p. 439) and the transliteration of Hunger (1992,
p. 173).

Translation
1 1 AN-e—SA₅ ma-ḥi-ši [HE.GAL ina—KUR GÄL-ši]

(The translation of 2-r.7 is omitted)

r.8 ša“GA-kir

Appendix C
Comparable Auroral Reports During the Known Space
Weather Events

As premordern auroral reports are frequently vague and
subject to critical analysis (Silverman 2006; Usoskin et al.
2017), it is always important to reference parallel auroral
reports during known space weather events (Stephenson et al.
2019).

In tablet R1 (tablet Rm211), the “red glow (akukātu)” was
reportedly blazing at the zenith and moved from south to north,
as associated with a south wind. Likewise, in tablet R3 (tablet
80-7-19,19), it was reported: “red covers the sky (AN-e—SA₅
ma-ḥi-ši).” Although aurorae in mid to low latitudes are
frequently expected along the equatorward horizon, aurorae
during extreme space weather events can reportedly cover the
entire sky and even show poleward retreat.

On 1872 February 4, an extreme space weather event caused
global auroral displays visible down to ±19° or even more
equatorward (Silverman 2008). Hall (1872) reported an auroral
display at Barnstaple (N51°05′, W00°04′; 55°0 MLAT) as
follows: “About 6 p.m., while it was still twilight, a patch of
red diffused light was observed near Orion’s belt. Up to 6.55,
no auroral light was distinguishable in the northern portion of
the sky; but at that moment there was a sudden outburst of rays
from the central point, covering the entire heaven in every
quarter, several of the ray’s in the E. and E.N.E. being,
however, especially remarkable for their width and color.”
Here, an aurora was first seen in the southern portion of the
sky and then covered the entire sky. This report is similar to the
auroral report at London (N51°37′, W00°08′, 55°0 MLAT): “in
the southwest there was an intense glare of red covering a
very large extent” (Loomis 1860, p. 389). These descriptions are
comparable with those in R1 and R3.

Tablet R2 (K748) reported the “red cloud (erpetu(IM.DIRI)
sämtu(SA₅))” being placed in the sky. Aurorae were frequently
described as a “red cloud” even in early modern observations.
Reporting the space weather event on 1859 August 28, which
precedes the famous Carrington storm (Tsurutani et al. 2003;
Cliver & Dietrich 2013), William Dawson in Henry Co.,
Indiana (N40°00′ W85°15′, 50°6 MLAT), states as follows:
“August 28th, about 9 P. M. a red cloud covered a large portion
of the eastern sky with a similar one in the N. W.” (Loomis 1860,
p. 345). This report is also consistent with the description of a
red cloud in R2.

Considering their relatively long duration, SAR arcs are
plausible in this case, as they are broad in shape and last for
more than a few hours without significant motion (Kozyr et al.
1997). A red-dominated aurora is also a possible candidate
(Miyaoka et al. 1990). Otherwise, the report may refer to
volcanic aerosols, although Mesopotamia is far from active
volcanoes.

Tablet R3 (tablet 80-7-19,19) reported “red covers the sky.”
Although this text is very short, the coverage of redness in the
sky is consistent with auroral displays covering a large part of
the sky, either by SAR arcs or normal red aurorae (see, Miyaoka et al. 1990; Kozyra et al. 1997).

These parallel reports demonstrate that the candidate auroral observations in the Assyrian astrological reports are consistent with early modern visual auroral observations during known space weather events. Given that the MLATs of Assyria and Babylonia were ≈8° more poleward than those in modern times (see Figure 3), it is plausible that the auroral displays were seen more frequently and more dramatically in these regions in the early 7th century BCE.

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