The star that stopped: The Star of Bethlehem & the comet of 5 BCE

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This study introduces a comet candidate to explain the Star that the Magi associated with the birth of Jesus as described in the biblical book of Matthew. By utilising observations of a comet recorded in Chinese annals in 5 BCE, a novel numerical technique was used to compute an orbit for this comet that could have passed very close to Earth in early June of 5 BCE, exhibiting 'temporary geosynchronous' motion. This is the first astronomical candidate for the Star ever identified that could have had apparent motion corresponding to the description in Matthew, where the Star 'went before' the Magi on their journey to Bethlehem until it 'stood over' where the child Jesus was. The study also examines how the Magi may have been influenced by ancient beliefs about comets, as described in Greco-Roman astrological writings, contemporary cuneiform omen texts, and the belief system of astrological geography. There is also a discussion of how this comet candidate corresponds to the chronology of the events surrounding Jesus' birth.

Introduction

The mystery of the Star of Bethlehem has captured imaginations for millennia. More than 400 books and papers have been published on the subject by scientists, historians and theologians, yet a key question remains unanswered: was the Star said to be observed by the Magi at the time of Jesus' birth a real physical astronomical phenomenon in the Judean skies?

The chief difficulty in identifying the Star as an astronomical event lies in explaining its unusual behaviour, as described by Matthew: 'the star, which they saw in the east, went before them, till it came and stood over where the young child was'. Many of the various astronomical theories proposed, such as planetary conjunctions, meteors, and novae/supernovae, are not known to behave in this seemingly unphysical manner. This has often led to one of two conclusions: to assume the Star was miraculous in nature, or to consign the entire story to the category of religious myth. But is it true, as many scholars have concluded, that no astronomical object behaves this way?

In this study, a comet candidate is proposed for the Star of Bethlehem based on a previously identified observation recorded by ancient Chinese astronomers in 5 BCE – a date consistent with estimates of the birth date of Jesus. Using a novel numerical technique, the imprecise observations by the Chinese astronomers were analysed to generate a family of candidate comet orbits, a subset of which show behaviour that conforms to the puzzling motion of the Star identified by Matthew.

In conjunction with this astronomical analysis, ancient astrological beliefs and other historical and cultural information are examined to piece together a plausible story of how this comet could have convinced the Magi to make their long journey to Judea in search of a newborn king.

The story of the Star of Bethlehem

The first issue that must be addressed is the source material for the story of the Star. The second chapter of Matthew (2:1–16) is the only biblical passage – and the primary literary source – that describes the events surrounding the Magi's journey to Judea and their observations of the Star. The book of Matthew was probably written sometime in the second half of the first century CE, which means its author was likely not an eyewitness to the events of the nativity. If the Star's story is based on a real historical event, then the author of Matthew presumably drew on a contemporary oral or written source. The question of Matthew's authorship is a complex subject beyond the scope of this paper. However, because this authorship is not critical to the Star's story, this paper will simply refer to the author as 'Matthew'.[1]

The first two chapters of the biblical book of Luke also present a birth narrative for Jesus, but Luke mentions neither the Magi nor the Star. Several chronological and contextual challenges arise when comparing the birth narratives in Luke and Matthew, but these are too complex to address here.[2,3] For the purposes of this paper, only the chronology in Matthew and how it relates to the timeline of the Star is considered.

The Greek texts analysed in the following are the *Novum Testamentum Graece* (Nestle-Aland 2012) and the United Bible Society Greek New Testament (Aland *et al.*, 2011).[4,5] These are the standard composite texts used by biblical scholars and represent the best reconstruction of the New Testament's original text based on the large number of extant Greek manuscripts. While the text of Matthew is perhaps the best preserved of the four biblical gospels, there are two important textual variants for this passage preserved in the manuscripts, which are discussed later in this paper.

The English text here is taken from the Authorised Version (AV), also known as the King James Version.

> 1 Now when Jesus was born in Bethlehem of Judaea in the days of Herod the king, behold, there came wise men from the east to Jerusalem,
>
> 2 Saying, Where is he that is born King of the Jews? for we have seen his star in the east, and are come to worship him.
>
> 3 When Herod the king had heard these things, he was troubled, and all Jerusalem with him.
>
> 4 And when he had gathered all the chief priests and scribes of the people together, he demanded of them where Christ should be born.
>
> 5 And they said unto him, In Bethlehem of Judaea: for thus it is written by the prophet,
>
> 6 And thou Bethlehem, in the land of Juda, art not the least among the princes of Juda: for out of thee shall come a Governor, that shall rule my people Israel.
>
> 7 Then Herod, when he had privily called the wise men, enquired of them diligently what time the star appeared.
>
> 8 And he sent them to Bethlehem, and said, Go and search diligently for the young child; and when ye have found him, bring me word again, that I may come and worship him also.
>
> 9 When they had heard the king, they departed; and, lo, the star, which they saw in the east, went before them, till it came and stood over where the young child was.
>
> 10 When they saw the star, they rejoiced with exceeding great joy.
>
> 11 And when they were come into the house, they saw the young child with Mary his mother, and fell down, and worshipped him: and when they had opened their treasures, they presented unto him gifts; gold, and frankincense and myrrh.
>
> 12 And being warned of God in a dream that they should not return to Herod, they departed into their own country another way.
>
> 13 And when they were departed, behold, the angel of the Lord appeareth to Joseph in a dream, saying, Arise, and take the young child and his mother, and flee into Egypt, and be thou there until I bring thee word: for Herod will seek the young child to destroy him.
>
> 14 When he arose, he took the young child and his mother by night, and departed into Egypt:
>
> 15 And was there until the death of Herod: that it might be fulfilled which was spoken of the Lord by the prophet, saying, Out of Egypt have I called my son.
>
> 16 Then Herod, when he saw that he was mocked of the wise men, was exceeding wroth, and sent forth, and slew all the children that were in Bethlehem, and in all the coasts thereof, from two years old and under, according to the time which he had diligently inquired of the wise men.

From this simple text, pious legend and popular imagination have added much to the story. It will be necessary to peel away these layers and look at the text with fresh eyes to identify a possible historical astronomical candidate for the Star of Bethlehem. The Greek text of Matthew, with some detailed analysis, gives several clues to the nature of the Star.

2:1 *Herod* – known as 'the Great', he ruled Judea as a Roman client king from 37 BCE to 4 BCE (more on his reign and the chronology in the section 'The comet theory'; see page 390). This establishes the initial time estimate for the events of Matthew 2.

2:1 *wise men* – the term often translated 'wise men' in 2:1 and 2:7 is the ancient term 'Magi' (μάγοι, *magoi*), a group of people well known in the ancient world, though their exact roles over time are unclear. The biblical text does not specify the number of Magi, though tradition has assigned the number three – presumably to correspond to the number of gifts offered to the child Jesus (Matthew 2:11). According to Greco-Roman sources, the Magi were originally one of the tribes of the Medes (Herodotus 1.101; Strabo 15.3.1) and served as priests (Strabo 15.3.14–15; Xenophon, *Cyropedia* 4.5.14, 7.5.57) and diviners (Cicero, *De divinatione* 1.41; Plutarch, *Alexander* 3.7).[6–11] In addition, according to both Greek and biblical sources, the Magi had a reputation for oneiromancy (the interpretation of dreams; Herodotus 1.107, 120, 128; Cicero, *De divinatione* 1.23; Plutarch, *Alexander* 18.6; Matthew 2:12). By the time of Jesus' birth, the Magi's role had evolved, and their exact relationship to other groups in the ancient Near East often associated with them – such as the Chaldean astronomer/astrologers and Zoroastrian priests – is much more difficult to disentangle, and beyond the scope of this study. However, as van Kooten (2015) has shown, contemporary Greco-Roman sources are quite clear that the Magi had a reputation as astrologers.[12] They were also considered to be 'kingmakers', and often involved in selecting and endorsing a new sovereign.[13] Both of these roles help explain the Magi's presence in Matthew's narrative.

2:1 *from the east* – ἀπὸ ἀνατολῶν (*apo anatolōn*) is the plural anarthrous form and indicates geography (cf. Matthew 8:11, 24:27), which, from the viewpoint of Jerusalem, meant they were probably from the Parthian Empire, perhaps from the royal court in the satrapy of Babylonia or Persia.

2:2 *King of the Jews* – βασιλεὺς τῶν Ἰουδαίων (*basileus tōn Ioudaiōn*), literally 'King of the Judeans'. Matthew's words seem to indicate that the Magi were simply looking for a new heir to the Judean throne, not necessarily an eschatological Messiah figure.

2:2 *for we have seen* – The verb εἴδομεν (*eidomen*) here (also in 2:9) is in the aorist, not in the perfect as it is translated in the AV. It can mean 'we saw' or (perhaps more appropriate for astronomers) 'we observed'. The meanings of aorist verbs in Koine Greek can sometimes be ambiguous.[14,15] The primary meaning of an aorist is constantive – describing an action in its entirety without chronological detail. However, there are times when the aorist is used in a more detailed way. A punctiliar aorist means the event occurred once in the past, as in 'we saw/observed once'. This is often how this passage is interpreted – that the Magi had a single observation of the Star. However, an aorist might instead bear an ingressive meaning, which focuses on the start of an action that then continues. In that case, it could mean 'we began to see/observe'. Further context is needed to determine which meaning was intended.

2:2 *his star* – The use of the singular 'his star' (αὐτοῦ τὸν ἀστέρα, *autou ton astera*) seems to indicate a solitary astronomical object (as opposed to a conjunction of multiple objects). In the ancient world, the term 'star' had a wider range of meaning than in modern times. To the ancients, 'star' meant any light in the sky, including planets ('wandering stars') and comets ('hairy stars').

2:2 *in the east* – As many scholars have pointed out, the arthrous singular form of ἐν τῇ ἀνατολῇ (*en tē anatolē*) here is most likely used as an astronomical term meaning 'at its rising' or 'when it rose' (cf. Jdg 5:31 in the Greek Septuagint).[16,17] Hughes (1979) believes this refers to the acronychal rising of the star,[18] and Molnar (2015) believes this specifically refers to the heliacal rising, times thought to be of astrological significance when an object rises relative to the position of the Sun.[19] However, as Heilen (2015) points out, the phrase could simply refer to the standard rising of any astronomical object in the east due to the Earth's diurnal motion.[20] This use of astronomical terminology seems to indicate that Matthew believed he was reporting on an actual astronomical object.

2:2 *to worship him* – the word translated 'to worship' here (προσκυνῆσαι, *proskunēsai*) is often assumed to imply the Magi's belief in the deity of Jesus. In the context of the cultural norms of the Parthian Empire, however, it can simply refer to showing proper homage to a royal figure.[21]

2:3 *he was troubled* – one common assumption is that this verse indicates the Star was unknown to Herod, excluding the possibility of a spectacularly bright candidate for the Star. The word here for 'troubled' is ἐταράχθη (*etarachthē*), meaning Herod and the people were 'disturbed' and 'unsettled' by the news of the Magi. Herod, now some 70 years old, was notorious for his paranoia, to the point of executing his own sons.[22] In addition, the Parthians had been Herod's enemies when they captured Jerusalem in 40 BCE and supported his Hasmonean rival, Antigonus.[23] It is reasonable to conclude that it was the Magi's unexpected arrival (if they were indeed Parthian) and/or their *interpretation* of the Star's appearance (that it foretold a new king of the Judeans), and not the Star's existence itself, that upset him. Therefore, this text does not necessarily reveal anything definitive about whether the Star was visible to anyone other than the Magi.

2:4 *where Christ should be born* – however the Magi interpreted the birth of the new Judean king, Herod seems to have been afraid they were announcing the birth of the long-awaited Messiah (ὁ Χριστὸς, *ho Christos*).

2:7 *what time the star appeared* – Herod enquired about τὸν χρόνον τοῦ φαινομένου ἀστέρος (*ton chronon tou phainomenou asteros*), literally 'the duration of the appearing star'. Φαινομένου (*phainomenou*) often refers to 'becoming manifest' or 'appearing' but can also denote 'shining' or even 'rising and shining'.[24] Thus, Matthew may have meant to link the 'appearing/rising star' to the Magi's description of the Star 'when it rose'. φαινομένου (*phainomenou*) is a present adjectival participle, indicating ongoing activity; that is, the Star continued to appear/rise. While the interpretation of the aorist εἴδομεν (*eidomen*) described previously is often ambiguous, that of the present participle is not. This verse is therefore consistent with an ingressive interpretation for εἴδομεν: the Star began rising at some point in the past and continued to rise, perhaps each night.

The phrase τὸν χρόνον (*ton chronon*) indicates a 'span of time' or 'duration', which means Herod was enquiring how long this 'appearing star' had been visible.[25,26] Matthew says (2:16) that later Herod tried to execute the male children of Bethlehem 'two years old and under' (ἀπὸ διετοῦς καὶ κατωτέρω, *apo dietous kai katōterō*). This seems to indicate (at a minimum) multiple weeks or months had passed since the Magi first observed this star 'when it rose' (See the section 'Cultural and astrological context for the comet theory' on page 399 for a discussion of the chronology of the 'slaughter of the innocents' passage).

One possible interpretation, then, is that the Magi began to observe the Star rise some months beforehand – perhaps even a heliacal rising. Then they continued seeing it rise nightly until they reached Jerusalem, rather than the Star appearing only once in the past then disappearing for a time.

While the text is not explicit regarding the Magi's location when they first observed the Star, the overall passage (2:1–2, 7, 16) indicates they first observed it while still in their own country, whence they began their journey ('from the east'). Using modern mapping software, it is possible to calculate a journey from, for example, Babylon to Jerusalem, which takes approximately 254 hours on foot, or some 30 eight-hour days. A similar trip starting from Persepolis in Persia takes 435 hours, or 55 days.

Contrary to popular belief, there is no indication in the text that the Magi 'followed' the Star on this first leg of their journey, or that it otherwise indicated direction to them like a 'celestial GPS'. Apparently, something other than the Star's azimuth in the sky made the Magi believe it was associated with the birth of the King of the Judeans and convinced them to begin a journey to Jerusalem.

2:9 *the star, which they saw in the east* – ὁ ἀστὴρ ὃν εἶδον ἐν τῇ ἀνατολῇ (*ho astēr hon eidon en tē anatolē*), 'the star which they observed/began to observe when it rose'. Matthew indicates this was the same star they had seen when they began their journey (2:2).

2:9 *went before them* – προῆγεν αὐτούς (*proēgen autous*). The word προῆγεν (*proēgen*), the imperfect form of προάγω (*proagō*), means 'was going before', or 'was preceding'. This is how Matthew uses the word in other passages within his Gospel (14:22, 21:9, 21:31, 26:32, 28:7). The direct object of the verb is 'them', indicating that Matthew was describing the Star motion in relation to the Magi, not describing some generic motion against the background stars,[27] *contra* Bulmer-Thomas (1992).[28] Matthew seems to indicate that the Star's location was directly in front of the Magi as they made their way to Bethlehem, as if it was travelling in advance of them. However, even though this could be understood as the Star 'leading' the Magi, Matthew never explicitly states that the Magi relied on the Star's location or motion for navigation.

The direction from Jerusalem to Bethlehem is slightly west of south (the road is relatively straight, with azimuth ~206°).

Modern mapping software indicates that the walking time from Jerusalem to Bethlehem is approximately two hours, depending on the starting location within Jerusalem and whether the travellers were burdened by baggage or there was heavy traffic. Two or three hours is a reasonable allowance for the journey, during which it should be expected that any astronomical candidate for the Star of Bethlehem would maintain an azimuth near 206°.

2:9 *till it came and stood over where the young child was* – ἕως ἐλθὼν ἐστάθη ἐπάνω οὗ ἦν τὸ παιδίον (*heōs elthōn estathē epanō hou ēn to paidion*). As the Magi approached Bethlehem, the Star apparently moved into a position directly over the location where they found Jesus: 'Arriving' (the singular masculine aorist participle ἐλθὼν, *elthōn* means the Star's arrival, not the Magi's), the Star 'stopped'. The verb Matthew uses here is ἐστάθη (*estathē*), the aorist passive form of *ἵστημι* (*histēmi*), which when used in the intransitive means 'stopped' or 'stood still'.[29]

The preposition for 'over' is ἐπάνω (*epanō*), a compound of the preposition ἐπί (*epi*) meaning 'on', or 'over', plus the adverb ἄνω (*anō*) – 'above' or 'upward'.[30] Like most prepositions, it has a spectrum of meanings. It is sometimes used in a 'weakened' sense to mean 'upon', which is how Matthew often uses it (5:14, 21:7, 23:18, 23:20, 23:22, 28:2).[31] In this passage (and in Matthew 27:37), it appears to mean something like 'up above' or 'directly over'. See also Luke 4:39 for a similar construction. According to Heilen (2015), 'The word denotes a position vertically above the place without specifying the distance.'[32] In the Septuagint – the Greek translation of the Jewish scriptures that greatly influenced the New Testament writers' Greek style – there is an even wider semantic range for ἐπάνω (*epanō*). Several verses use the preposition in an astronomical or quasi-astronomical sense (Genesis 1:2,7, Psalms 108:4, Isaiah 14:13,14). In some of these verses, the word indicates considerable height, not only a short distance. See also the discussion in Panaino (2015).[33]

The language of the text here is somewhat imprecise on one point: it only says that the Star stopped 'over where the child was' (ἐπάνω οὗ ἦν τὸ παιδίον, *epanō hou ēn to paidion*) using the vague relative pronoun 'where' οὗ (*hou*).[34] Only after two more verses (in 2:11) does Matthew indicate that the child was located in a house along with his mother. It is possible that Matthew meant that somehow the Star indicated the location of the actual house (an ability that would probably preclude any natural astronomical object), but it is not explicitly stated nor required by the text. In fact, the text is not at all clear on how the Magi identified the house where the new king was located. Matthew says that Herod instructed the Magi (2:8) to 'make a careful search for the child' (ἐξετάσατε ἀκριβῶς περὶ τοῦ παιδίου, *exetasate akribōs peri tou paidiou*), and presumably that is what Matthew wanted his readers to understand that they did.

The passage indicates that after the Star appeared to precede the Magi on their short journey to Bethlehem, it reached a position over the town, perhaps overhead near the zenith, where its motion came to a noticeable stop for a period coincident with their arrival. Cullen (1979) states the implications of this passage very succinctly: 'This implies an object which increased its altitude [i.e., elevation angle] markedly in a matter of hours while maintaining a constant southerly azimuth'.[35]

The word for child here is παιδίον (*paidion*, 2:8,11), which can refer to a child up to several years old (cf. Matthew 11:16). This word is often used by scholars to infer that the visit of the Magi was a long time after Jesus' birth. However, Luke, who uses the word βρέφος (*brephos*) to describe the infant Jesus at his birth (2:16), uses the word παιδίον (*paidion*) to describe John the Baptist when he was circumcised on the eighth day (1:59). Therefore, the wide semantic meaning of the word does not provide precise information on the age of Jesus when the Magi arrived, but only that the Magi arrived sometime after Jesus was born – perhaps any time between a few days and two years.

The comet theory

The problem

A survey of the literature shows that virtually every conceivable astronomical object has at one time been proposed as the Star of Bethlehem.[36] However, it has long been recognised that Matthew 2:9 presents a particular challenge: the 'going before' and 'stopping' behaviour does not seem to conform to the motion of any known natural celestial object. Typical astronomical objects – stars, planets, comets – appear to rise in the east and set in the west, due to the diurnal rotation of the Earth. Such objects do not normally pause at a particular southerly azimuth for several hours, nor would they typically 'stop' overhead for any length of time. This raises difficulties for theories that try to explain the Star using planetary alignments or stellar phenomena, both of which have been popular candidates. Adair (2014) states this issue clearly: 'the key problem is that the description of the movements of the star is outside what is physically possible for any observable astronomical object'.[37]

This strange, apparently non-astronomical behaviour has generally forced scholarship and speculation on this subject into three general categories:

- *Theological interpretation:* The story is regarded as embellished, perhaps as a myth or midrash created to make a theological point, meaning there was never any physical Star of Bethlehem. If this is the case, seeking an historical astronomical explanation is a futile exercise.[38]

- *Miraculous interpretation:* Matthew's account is accepted at face value, with the Star considered miraculous – a belief held by many Church Fathers. However, while Matthew clearly believed that God directed the events, the text provides no indication that he regarded the Star as anything other than a physical object. A miraculous explanation also negates any need to find a natural candidate.

- *Natural phenomenon with textual reinterpretation:* The Star is accepted as a natural astronomical event, but the text is then allegorised or adjusted. If one has chosen a favourite astronomical explanation, the meaning of the text is reinterpreted to force it to match the known behaviour of the astronomical phenomenon.

An example of this 'allegorising' tendency is when astronomers assume Matthew's description of the Star 'stopping over the place where the child was' refers to the pausing of a planet at its transition between prograde ('direct') motion and retrograde motion.[39] Panaino (2015) and Heilen (2015) thoroughly examine this claim and show that grammatically such a translation does not seem tenable.[40,41]

A different type of 'allegorising' is used by Humphreys (1991), who points to other Greek texts of the same general period to show that the behaviour of a comet can be described using language similar to Matthew's.[42] The two ancient sources he quotes describe comets as being 'over' a city. However, the preposition used in these passages is ὑπὲρ (*huper*, meaning 'over' or 'beyond'). It can mean 'above' in a general sense, which could apply to almost any object in the sky, not just comets. Nor does either passage ascribe unusual motion to the comet. While these comet passages are vivid descriptions of the phenomena, they lack the specificity of the language employed in Matthew to describe the motion of the Star.

Nicholl (2015) interprets the Star's 'stopping' behaviour as the pointing of a tailed comet, low in the sky, toward a specific house located on the horizon.[43] However, interpretations of this type do not seem to match Matthew's description indicating the Star was in a vertical position 'directly over' Bethlehem.

The approach of this paper is to assume that the text of Matthew is an accurate, straightforward description of a natural astronomical phenomenon. The paper will examine an astronomical candidate to see if this assumption is credible, and in doing so perhaps shed light on the reliability of this passage as an historical source.

On whether astronomical objects can 'stop' overhead

Many researchers have concluded that because no known astronomical object behaves this way, no natural explanation is possible. However, the next part of this paper will introduce an astronomical phenomenon that could have acted like the Star, as described in Matthew.

Before going further, it is useful to summarise the main features of Matthew's narrative concerning the Star's nature:

– Magi astronomer/astrologers from the east – probably within the Parthian Empire – first observed a star (probably while they were still located in the eastern realms) 'when it rose'.

– For some reason, they concluded that this was the Star heralding the birth of a new king of the Judeans and were convinced to begin a journey to Jerusalem.

– They most likely continued to observe the 'appearing star' as they trekked to Jerusalem, but there is no indication that it 'led' them or otherwise indicated direction.

– They arrived in Jerusalem many weeks after they made their initial observations.

– When news reached Herod that these Magi had arrived, and that they interpreted the appearance of the Star as indicating the birth of a king, this upset the unstable Herod, but there is no indication that Herod or the people of Jerusalem were ignorant of the Star's existence.

– The Magi were instructed by Herod to go to Bethlehem to search for the new king, based on the interpretations of a biblical prophetic text his religious scholars shared with him.

– While on the road to Bethlehem the Magi once again observed the Star, which this time was in front of them as they travelled, staying at an azimuth just west of south for several hours and gradually gaining in elevation, until it reached a position nearly overhead, where it appeared to 'stop' for some time when they arrived at their destination in Bethlehem.

– Based on the duration of the Star's observations reported by the Magi, Herod ordered all male children around Bethlehem 'two years old and younger' to be killed.

A central question is whether an astronomical object can appear to 'stop' directly over a location on the rotating Earth. Certain artificial satellites are launched into circular orbits whose period matches the planet's rotation rate. Such geosynchronous satellites appear to continuously 'stand' over a particular location on the Earth's equator. Similarly, satellites are sometimes launched into high-eccentricity Molniya orbits, allowing them to appear temporarily 'geosynchronous' and 'pause' near the zenith for several hours from the perspective of observers at certain high-latitude locations on Earth.[44]

While it is unlikely that the Star of Bethlehem was an object in Earth orbit, if an interplanetary object were to travel past Earth at the right speed, direction, distance, position and time, it would be possible for the motion to temporarily match and counter Earth's rotation rate. Such an object might appear to temporarily 'stop' directly over a particular geographic location for several hours as it passed by (see Figure 1). We might refer to such an

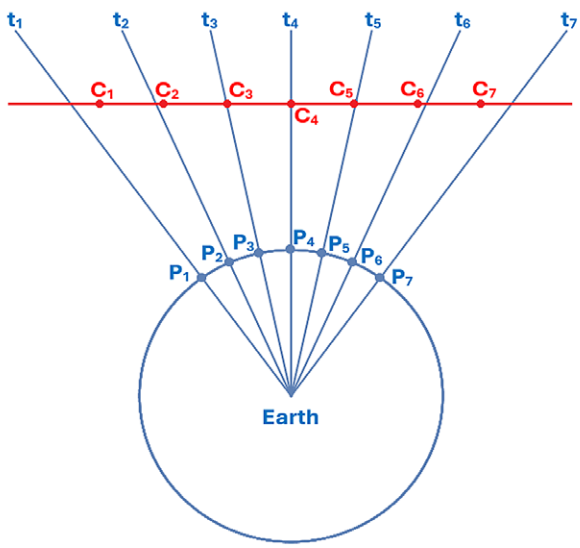

Figure 1. This is a simplified diagram of a hypothetical interplanetary object ('C') travelling near Earth. The subscripts refer to its position at time steps t_1 to t_7. For a fixed position ('P') on the rotating Earth, the object would appear to remain stationary directly overhead as a 'temporary geosynchronous object' for several hours (t_3 to t_5)..

unusual occurrence as 'temporary geosynchronous motion'. For an observer at Bethlehem (31.7° N), the object would need to be travelling eastward at ~13°/hour for this to occur. For typical velocities of objects moving through the inner solar system, an object would need to come unusually close to Earth – within about 1.2 × 10^6 km – for this to happen.

Planets are too distant from Earth to exhibit this behaviour. Asteroids sometimes travel very close to Earth; however, they are typically very dark and difficult to observe without a telescope, even when nearby. The only likely solar-system candidate for a temporary geosynchronous object that would be easily visible for an extended period is a comet. While several known periodic comets exist, bright long-period comets appear only a few times each century. Because their long orbital periods can span millennia, some may be observed only once in human history, often unpredictably. Moreover, a comet's coma and tail can remain bright enough to be visible for many weeks or even months.

An example of a comet that came close to Earth is C/1996 B2 (Hyakutake). On 1996 Mar 25, it passed Earth at a distance of 0.10 au (1.5 × 10^7 km; the astronomical unit, au, is the average Sun–Earth distance), at which time it exhibited a motion of ~0.5° per hour against the background stars for a few hours – a very high angular speed for a comet. For a hypothetical comet to appear to 'stop' over Bethlehem, it would need to come even closer, by a factor of 10 or more. Another example of a close approach occurred on 2014 Oct 19, when comet C/2013 A1 (Siding Spring) passed within 141,000 km (9.43 × 10^{-4} au) of Mars – a third of the Moon–Earth distance.[45] So, while rare, such close approaches are possible.

A comet as a candidate for the Star of Bethlehem

Numerous authors have speculated that the Star was a comet. Some have identified the appearance of Halley's Comet in 12 BCE as a possible candidate.[46,47] However, this is generally believed to be too early for Jesus' birth. Others link it to the appearance of Halley's Comet in 66 CE, near the time of composition of Matthew's gospel, 'back-projected' to the birth of Jesus.[48] Nicholl (2015) proposed a detailed hypothetical comet orbit to explain the Star. However, his proposed orbit is based on no historical astronomical observations that might corroborate the existence of his comet.[49]

Panaino (2015), however, rejects the possibility that Matthew's star was a comet, claiming that a Greek writer would never use the term ἀστήρ (*astēr*) alone without the modifier κομήτης (*komētēs*) to describe one.[50] While Greek writers often did combine the two, this was not universal. Ramsey & Licht (1997) give multiple quotations by both Greek and Latin authors describing 'Caesar's comet' of 44 BCE.[51] Many of these writers refer to that comet with the unmodified term ἀστήρ (*astēr*) or various Latin synonyms (*e.g.*, *sidus*, *astrum*). Clearly, then, a comet could be referred to as an ἀστήρ (*astēr*).

Further support comes from the discussion by the third-century church scholar Origen in his work *Contra Celsum* (1.58–59), in which he theorised that the Star was a comet, or at least the same kind (γένος, *genos*) of astronomical object as a comet.[52] The fact that Origen, an expert in Greek, saw no problem equating Matthew's unmodified ἀστήρ (*astēr*) with a comet strongly suggests that a comet explanation cannot be rejected purely on linguistic grounds.

Identifying a comet candidate for the Star of Bethlehem

While it is an interesting intellectual exercise to infer the close approach of a hypothetical comet based solely on Matthew's description, without precise observing dates or times there is insufficient information to construct a useful cometary orbit. Without an orbit, no convincing theory to explain the Star of Bethlehem can be constructed.

To construct a specific orbit, observational data from historical records are essential. But identifying relevant historical data first requires an approximate date for Jesus' birth. Determining this date is a complex historical problem, but Matthew makes it clear that the visit of the Magi – which occurred some length of time after Jesus was born – occurred while Herod the Great ruled Judea. The *terminus ad quem* for Jesus' birth is therefore Herod's death, usually dated to 4 BCE.[53,54,55] Most scholars consequently date Jesus' birth to around 6 or 5 BCE.[56]

Humphreys (1991), in his particularly strong case for a cometary explanation based on historical data, draws on a Chinese document known as the *Han Shu*, or *History of the Former Han Dynasty*, which is available online.[57,58] These historical annals preserve details of astronomical phenomena, often recorded for their presumed astrological significance, and include multiple observations of Halley's Comet and such events as solar eclipses. The astronomical events described in the *Han Shu* have been compiled into lists for use by modern astronomers.[59,60]

As Humphreys (1991) showed, the *Han Shu: Tianwen Zhi*, chapter 26 records an object about this time:

> '2nd year [of the *Chien-p'ing* reign of Emperor Ai of the Han Dynasty], 2nd month; a broom star [*hui hsing*] emerged in *Ch'ien Niu* for over 70 days.'[61,62]

The '2nd month' of the '2nd year' corresponds to the Chinese lunar month spanning 5 BCE Mar 9 to Apr 6, which falls neatly within the estimated window for Jesus' birth. Being visible 'for over 70 days' suggests that the object was likely bright.

Ch'ien Niu is a Chinese constellation of six stars that includes α and β Capricorni, located near the ecliptic. The name can also refer to the ninth Lunar Mansion – the 'Ox Lunar Mansion' – an ecliptic region about 8 degrees wide, bordered by β Capricorni to the west and ε Aquarii to the east, and extending some distance above and below the ecliptic.[63,64] However, the *Han Shu* reference appears to concern the six-star constellation rather than the Lunar Mansion. According to Ho (1966), *Ch'ien Niu* once referred to the constellation including β, α (Altair), and γ Aquilae, but during this period of the Han dynasty, Altair and these stars were known separately as *Ho Ku*.[65]

A *hui hsing* ('broom star') is typical Chinese taxonomy for a tailed comet. The so-called 'Cometary Atlas' found in the Mawangdui Han dynasty tombs, dated 168 BCE, preserves a diagram of a *hui hsing*.[66] The *Han Shu: Tianwen Zhi*, chapter 26 describes a typical (though different) *hui hsing* in some detail:

> 'Its body is like a star. Its end is like a broom (*hui*). It is 2 *zhang* [~20°] long.'[67]

When constraining the dates of the Star, it is important to note that the date of Herod's death is disputed. Some scholars argue for a later date of 1 BCE, while Hughes (1979) proposes an earlier date, in 5 BCE Dec.[68,69] For the purposes of this paper, the precise date is not critical. Broad scholarly agreement places Herod's death no earlier than late 5 BCE, making the Chinese comet observation a plausible candidate.

While many scholars have indeed suggested the Chinese observation as a possible candidate,[70,71,72] Hughes (1979), Kidger (2017) and others have questioned whether it was in fact a comet,[73,74] despite its clear identification as a 'broom star'. Comets typically move relative to the background constellations over days or weeks, rather than remaining near one constellation for an extended period. Because this object was observed in the same region of the sky for so long, they speculate that it was instead a bright nova or supernova. While this is a popular and attractive theory, such stellar phenomena do not move against the background stars, and therefore encounter the same drawbacks as planetary theories – they do not 'stop' over a particular location.

While most comets do appear to wander among the background stars as they move through the solar system, certain circumstances can make a comet seem to remain in one region of the sky for an extended period. Aircraft pilots have long known that if an object's angular position does not change relative to a moving observer, the object is likely on a path directly toward or away from that observer. This apparent lack of angular motion may therefore provide a clue to defining the object's orbit.

Making the reasonable assumption that this 'broom star' was indeed a comet, the fact that it maintained its position in a particular region of the sky 'for over 70 days' can be used to infer a plausible orbit. In their study of the comet that appeared in 44 BCE at the time of Julius Caesar's death, Ramsey & Licht (1997) demonstrated a method of combining imprecise observations reported in Roman literary sources to derive a family of possible cometary orbits.[75] They assumed that the 44 BCE comet was a long-period object with an orbital eccentricity close to 1.0 – corresponding to a near-parabolic trajectory – to constrain the orbit of 'Caesar's comet' and solve for a likely candidate. A similar parabolic assumption will be used in this paper.

Computation of a hypothetical comet orbit for the Star of Bethlehem

A numerical model was created to optimise a cometary orbit consistent with the Chinese observations of 5 BCE, by defining a quantitative metric to assess how well each candidate trajectory fit the data and then searching possible orbits to minimise this metric for the best fit.

The first step was to define the orbit as a state vector – comprising position and velocity – at a chosen reference time. Although this approach lacks the elegance of using Keplerian elements, it has the advantage of minimising the chance of numerical problems near problematic orbits, such as those with inclinations near zero. Assuming a parabolic orbit, the comet's speed is simply the escape speed v_{esc} at a radius r from the Sun

$$v_{esc} = \sqrt{\frac{2\mu}{r}} \quad (1)$$

where μ is the gravitational constant of the Sun. Therefore, only the direction of the velocity vector needs to be computed. The orbit was then defined by a position vector in space and the corresponding velocity vector at the reference time. This could easily be converted into orbital elements, and the parabolic orbit propagated to various times to determine the comet's apparent position in the sky as seen from Earth.

Although the Chinese observations are given with some detail, uncertainty remains in the comet's exact position. Association with a particular constellation constrains the location only within 5–10°, and only the month of the initial observation is known, not the precise day.

To make use of the Chinese data, a Monte Carlo technique was employed to sample the possible observation dates and positions. The initial observation date was chosen randomly from a uniform distribution between 5 BCE Mar 9 and Apr 6; this initial date also served as the reference time for orbit determination. Two additional sample dates were then selected: one +35 days and another +70 days after the initial observation, giving three sample dates to represent the reported '70 days' of visibility.

At each of the three sample dates, a position was chosen near the *Ch'ien Niu* constellation. The constellation's extent can be somewhat subjective, but for purposes of this model, a box was defined (Figure 2), spanning 270–280° in ecliptic longitude and −5 to 10° in ecliptic latitude (using the ecliptic of date). For each sample date, a random point was chosen within this box from a uniform distribution in right ascension and declination. How well the orbit fit the observation was determined by propagating the orbit to the three sample dates and computing the angular difference between the comet's direction vector and the chosen point at each date, using the arccosine of the vector dot product. The fit metric was defined as the sum of these three angular differences, and the optimum comet orbit is that which minimises this metric.

Optimisation was performed using a simple Simulated Annealing technique.[76] Orbit parameters were varied using a Monte Carlo technique, with acceptance or rejection governed by the following algorithm. Denoting the metric of the new orbit as φ_B and that of the previous orbits as φ_A, if $\varphi_B \leq \varphi_A$, the new orbit was accepted. If $\varphi_B > \varphi_A$, the acceptance criterion was computed as:

$$A = Exp\left[-\frac{(\varphi_B - \varphi_A)}{\mathcal{T}}\right] \quad (2)$$

where $\mathcal{T}$ is a 'pseudo-temperature' value . A random number R between 0 and 1 was generated, and if $R \leq A$, the new orbit was accepted. Otherwise, it was rejected, and a new test orbit was drawn using the same Monte Carlo technique.

At the start of the computation, a large $\mathcal{T}$ was used to allow the algorithm to 'explore' the multidimensional orbital space. As the computation progressed, $\mathcal{T}$ was gradually reduced toward zero so that the vectors converged on a global minimum optimal fit for each set of dates and pointings.

The following steps were used to generate an ensemble of possible orbits:

1) t_1 was chosen randomly from a uniform distribution between 5 BCE Mar 9 and Apr 6.

2) $t_2 = t_1 + 35$ days and $t_3 = t_1 + 70$ days were defined, and the Earth position vectors $\vec{R}_1$, $\vec{R}_2$, $\vec{R}_3$ were computed for those times.

3) Three random observation pointing normal vectors $\hat{y}_1$, $\hat{y}_2$, and $\hat{y}_3$ were selected in ecliptic coordinates (of date) at times t_1, t_2 and t_3 by choosing a sky position from a uniform distribution within the *Ch'ien Niu* box bounded as described previously.

4) An arbitrary reference position initial vector $\vec{r}_{1A}$ and normal velocity vector $\hat{v}_{1A}$ were chosen for the comet at reference time t_1. In addition, a suitably high initial $\mathcal{T}$ was assigned for use in the Simulated Annealing method.

5) The orbital elements of the comet were computed using the reference state vectors $\vec{r}_{1A}$ and $\hat{v}_{1A}$. For times t_1, t_2, and t_3, the corresponding position vectors of the comet $\vec{r}_1$, $\vec{r}_2$, and $\vec{r}_3$ were determined, together with the normal vectors

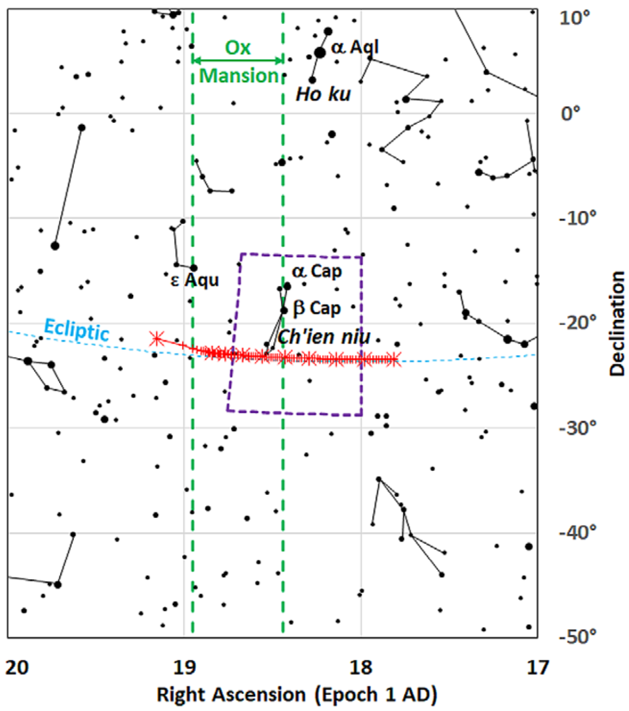

Figure 2. Star chart showing the path (in red) of the 5 BCE Jun 8 comet orbit as seen from Earth. The constellations depicted are those recognised during the Han period.[64] The comet path starts on the right at 5 BCE Mar 9, and moves slowly eastward (to the left). Tick marks represent one-day intervals, and each 'X' marks 10-day intervals, illustrating how the comet remained near the six-star *Ch'ien Niu* constellation for over 70 days. The purple box denotes the 'search box' described in the text. The green lines indicate the approximate limit of the Ox Lunar Mansion associated with *Ch'ien Niu*.

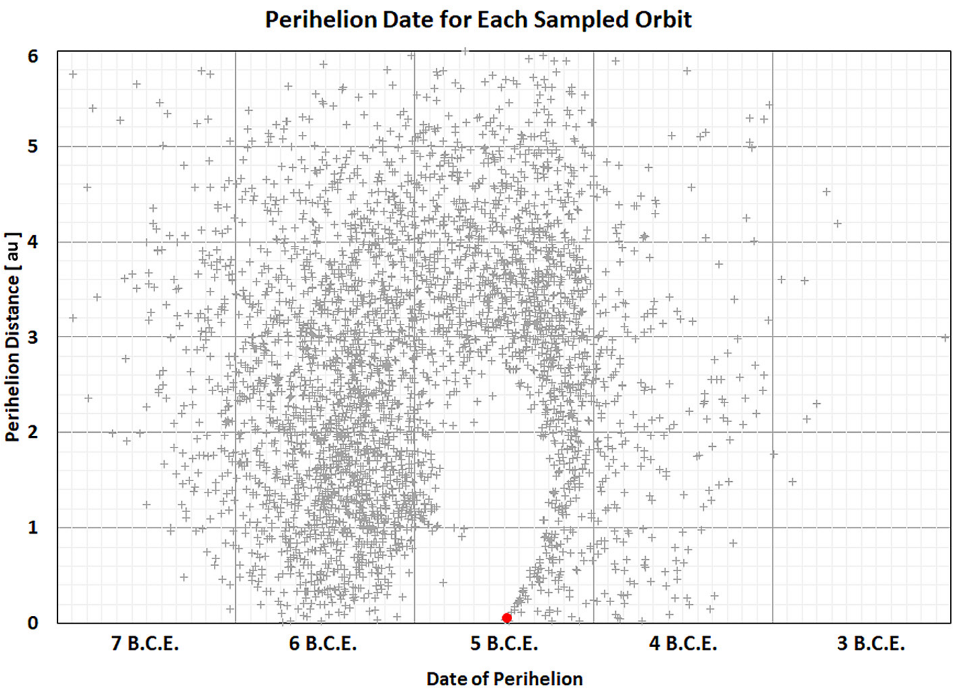

Figure 3. Samples of comet orbits that could explain the Chinese observations are plotted by perihelion distance and date of perihelion. Orbits on the left had already passed perihelion by the time of the Chinese observations in 5 BCE Mar, while those on the right reached perihelion after that date. The red dot marks the 5 BCE Jun 8 orbit discussed in the text, which reached perihelion in 5 BCE Jul.

pointing to the positions of the comet in the sky as viewed from Earth $\hat{n}_1$, $\hat{n}_2$, and $\hat{n}_3$ in ecliptic coordinates:

$$\hat{n}_1 = \frac{\vec{r}_1 - \vec{R}_1}{|\vec{r}_1 - \vec{R}_1|},\ \hat{n}_2 = \frac{\vec{r}_2 - \vec{R}_2}{|\vec{r}_2 - \vec{R}_2|},\ \hat{n}_3 = \frac{\vec{r}_3 - \vec{R}_3}{|\vec{r}_3 - \vec{R}_3|}$$

6) The metric φ_A was computed as the sum of the angular separations between the comet positions and the observation pointing vectors, using the dot products: $\varphi_A = \arccos(\hat{y}_1 \cdot \hat{n}_1) + \arccos(\hat{y}_2 \cdot \hat{n}_2) + \arccos(\hat{y}_3 \cdot \hat{n}_3)$.

7) A Monte Carlo method was used to vary the reference position vector to $\vec{r}_{1B}$ and normal velocity vector to $\hat{v}_{1B}$ by a small amount at reference time t_1. A new metric was then computed for this orbit, φ_B.

8) The Simulated Annealing method described above was used to decide whether to accept or reject the new orbit based on φ_A, φ_B and the current $\mathcal{T}$. If the new orbit was accepted, then $\vec{r}_{1A} = \vec{r}_{1B}$ and $\hat{v}_{1A} = \hat{v}_{1B}$; $\mathcal{T}$ was reduced by a small increment, and the process was repeated from step 5. If the new orbit was rejected, step 7 was repeated.

9) The comet's fitted orbital elements were recorded.

10) The process was repeated from step 1 to calculate additional orbits.

This method differed from standard orbit-determination methods in that no analytic estimate of the initial orbit was required; only an initial state vector – which in principle could be virtually anything – and a way to optimise the conformity to the measurements were needed. Because the observed positions are only known within a few degrees, this method would work well with a variety of ancient comet observations. Determining any orbit more complex than an idealised parabola would require much more precise positional data. Fortunately, for long-period comets, a parabolic orbit is an excellent approximation.

Scatter plots of the resulting cometary orbit parameters, such as the closest approach of each possible candidate comet to Earth, are shown in Figures 3 & 4. Some of these comets could have come quite close (<10^6 km) and are candidates for a comet that might behave in a temporary geosynchronous manner.

Selection of a comet orbit for the Star of Bethlehem

After careful examination of the Monte Carlo set of orbits, one solution gave intriguing results; it is highlighted in Figures 3 & 4.

Perihelion			q	= 0.0407 au
Eccentricity			e	= 1.0°
Inclination	i_{2000}	= 1.39°	i_{5BCE}	= 1.43°
Argument of perihelion	ω_{2000}	= 346.25°	ω_{5BCE}	= 335.58°
Ascending node	Ω_{2000}	= 93.01°	Ω_{5BCE}	= 75.81°
Date of perihelion	Tq	= 1719785.565 (Julian date)		
	ΔT	= +10,572 s		

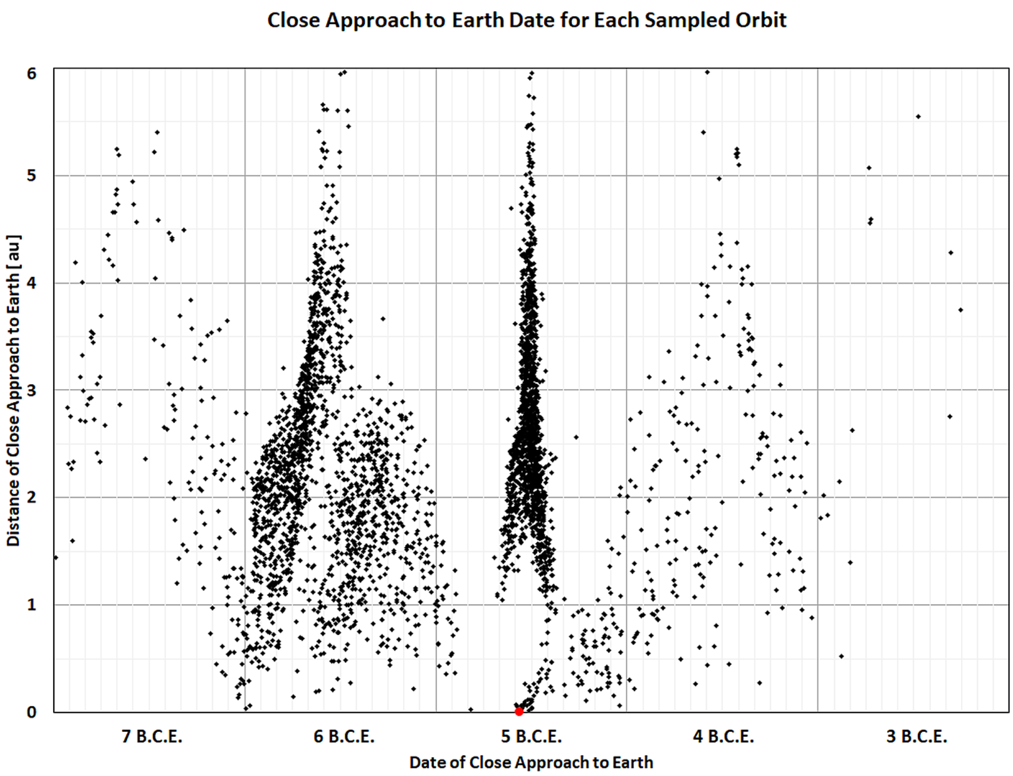

Figure 4. Orbit samples plotted by distance of closest approach to Earth and the date of that approach. The red dot marks the 5 BCE Jun 8 orbit discussed in the text.

The orbital elements are given relative to the ecliptic epochs J2000.0 and 5 BCE. The The difference between Terrestrial Dynamic Time and Universal Time ΔT, computed using the method of Espenak & Meeus (2006),[77] is used to determine the precise details of Earth's rotation. This comet's perihelion value indicates that it approached the Sun quite closely, thus categorising it as a sungrazing comet – though not a member of the Kreutz group. Its low inclination is consistent with a comet observed near the ecliptic for an extended period.

Using standard astronomical software, it was straightforward to input this comet orbit and display its path in the ancient sky.[78] Figure 2 shows a map of the comet path against the stars of 5 BCE. It maintains a position near *Ch'ien Niu* from mid-March to early June of 5 BCE (> 70 days). The definition of 'near' is a subjective metric, but this orbit appears to conform to the Chinese observations. A view from above the ecliptic plane (Figure 5) illustrates the geometry of the comet's orbit. Because of its low orbit inclination, a two-dimensional representation is useful and shows how, with this configuration, the comet maintained a nearly constant ecliptic pointing relative to an observer on Earth throughout the observed period.

This proposed orbit passes very close to Earth, with the closest approach occurring on 5 BCE Jun 8. On that day, the comet would have behaved in a most unusual manner as seen from Judea. Figure 6 shows the path of the comet in the Bethlehem sky on 5 BCE Jun 8. All times are given with respect to local noon – the instant when the Sun crosses the local meridian – corresponding to Julian date 1719755.898. In the following discussion, this orbit is referred to as the 'Jun 8 orbit' and the comet itself as the 'Jun 8 comet'.

The Jun 8 comet rose at around 22:00 local time on the evening of 5 BCE Jun 7, and remained visible for the rest of the night. When the Sun rose around 05:00 local time on Jun 8, the comet was at an azimuth just west of south. At approximately 08:00 local time, it reached its closest distance to Earth – 0.0026 au, roughly the Earth–Moon distance. As the comet neared Earth, its apparent angular motion against the background stars accelerated eastward, at a rate that approximately cancelled the effects of Earth's rotation. This caused the comet to appear to 'pause' in azimuth, as seen from Judea.

As the morning progressed, the comet maintained a nearly constant azimuth while rising in elevation as it passed by the Earth. Near 10:00 local time, it had reached a point only a few degrees from the zenith – almost exactly overhead – where it 'paused' until around 11:30. During this period of temporary geosynchronous motion, the comet remained virtually motionless over Bethlehem. By local noon, it had resumed westward diurnal motion, 'following' the Sun across the sky – and perhaps lost in its glare – until it set shortly after the Sun.

This motion is most extraordinary and would have been recognised as such by trained astronomical observers. Figure 6 shows a line indicating the approximate azimuth (206°) of the Jerusalem–Bethlehem road. The comet's azimuth remained within just a few degrees of this line during the morning of 5 BCE Jun 8, meaning that a traveller journeying from Jerusalem to Bethlehem would have seen the comet directly ahead. For a traveller arriving in Bethlehem around 10:00, the comet would have appeared to stop almost directly overhead for approximately two hours.

This analysis revealed that the Jun 8 comet orbit is not unique; it belongs to a family of orbits that match the Chinese observations

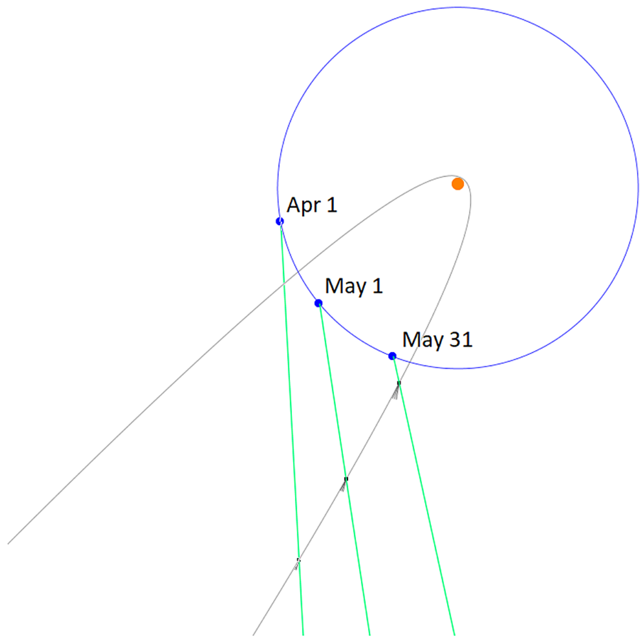

Figure 5. Schematic view of the 5 BCE Jun 8 comet orbit relative to Earth. The relative motion of the two orbits would have caused the comet to maintain a nearly constant ecliptic longitude when viewed from Earth for many weeks, remaining in the same region of the sky.

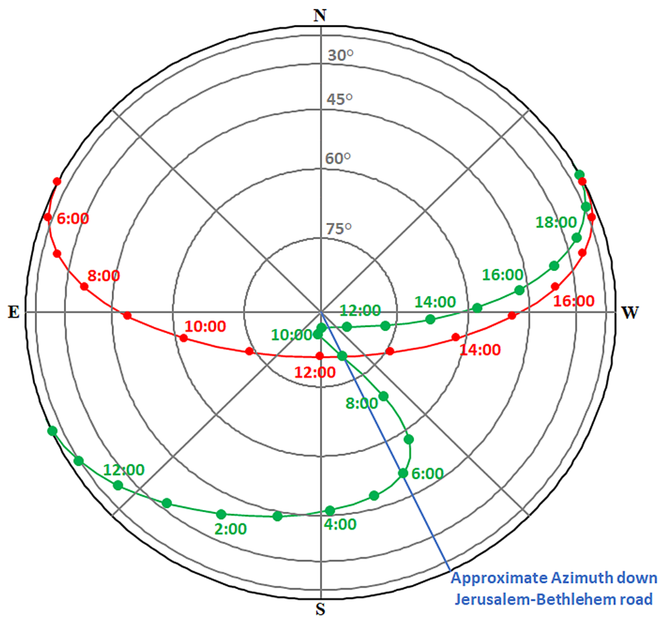

Figure 6. The path of the comet (in green) in elevation and azimuth as it would have appeared in the Jerusalem-Bethlehem sky on the morning of 5 BCE Jun 8. Times are referenced to local noon, when the Sun (red) crossed the meridian. The comet rose about 22:00 the previous night and was just west of south at sunrise. As it approached Earth, the comet maintained a nearly constant azimuth aligned with the road from Jerusalem to Bethlehem (blue) while climbing in elevation. By about 10:00, it reached a few degrees from the zenith, where it appeared to 'stop' for several hours.

while exhibiting similar 'going before' and 'stopping over' behaviour on the day of closest approach to Earth. These orbits have perihelion dates and orbital nodes shifted so that the close approach to Earth occurs at the same time of day and in the same manner as the Jun 8 comet, but on different dates. Tables 1 & 2 show a selection of these alternative orbits, with closest approach dates ranging from 5 BCE Jun 3 to Jun 13. All of these orbits are qualitatively similar to the Jun 8 orbit, with low inclinations and very close perihelion passes. The visit of the Magi could plausibly have occurred on any day between these dates, not solely 5 BCE Jun 8; however, the Jun 8 orbit best matches the Chinese observations and will be the orbit most commonly referred to in this paper.

Normally, a comet would not be visible during daylight hours, but the unusually close approach of this comet to the Earth would have made it extraordinarily bright. The apparent magnitude of a comet is a function of its position in the solar system, and can be approximated by

$$m = H + 5 \log_{10} \Delta + 2.5\, n \log_{10} r \qquad (3)$$

where Δ is the comet–Earth distance (au), n is the activity index, r is the comet–Sun distance (au) and H is the absolute magnitude – its brightness if it were 1 au from both Earth and the Sun.[79,80] Typically, n and H are determined empirically, but little direct information is available regarding this comet's brightness. Figure 7 shows a scatter plot of n and H values for historical comets.[81] Most comets have $n \sim 4.0$, but others are between about 2.0 and 6.0, with a typical minimum of $n = 2.5$.[82] The H values of such comets also exhibit a broad range, with only about 10 per cent of sungrazers having H brighter than about +2.[83]

The Jun 8 comet became visible to Chinese observers sometime between 5 BCE Mar 9 and Apr 6. Empirical evidence indicates that a comet must reach a visual magnitude of about +3.5 to be first noticed by ancient observers.[84,85] Once located, observers could likely have continued monitoring it even if it dimmed below +3.5, as long as it remained brighter than the limiting naked-eye magnitude of about +6.0. The bright Moon would have interfered with observations of a faint comet in Capricornus from about 5 BCE Mar 22–31, so it is possible to estimate that the candidate comet reached this threshold brightness in early March or early April.

Using this information, and testing several representative comet values for ranging from about 2.0 to 6.0, plausible comet brightness curves were constructed. Figure 8 shows the distance of the Jun 8 comet from both Earth and the Sun during 5 BCE,

Table 1. Comet orbits, later closest approach to Earth

Date of closest approach	Jun 9	Jun 10	Jun 11	Jun 12	Jun 13
ω_{5BCE} (°)	334.49	328.09	324.86	321.83	318.98
Ω_{5BCE} (°)	76.48	79.28	80.90	82.40	83.76
i_{5BCE} (°)	1.76	0.62	0.49	0.41	0.36
ω_{2000} (°)	343.11	353.17	356.77	359.82	2.15
Ω_{2000} (°)	95.74	82.07	76.85	72.27	68.46
i_{2000} (°)	1.71	0.60	0.47	0.40	0.36
q (au)	0.0456	0.0637	0.0752	0.0872	0.0997
T_q *(Julian date)*	1719786.754	1719788.442	1719789.866	1719791.298	1719792.739

Alternative comet orbits that match the Chinese observations and exhibit the 'going before' and 'stopping over' behaviour of the Jun 8 comet, but with the closest approach to Earth shifted to later dates. The orbital parameters are defined on page 395.

Table 2. Comet orbits, earlier closest approach to Earth

Date of closest approach	Jun 3	Jun 4	Jun 5	Jun 6	Jun 7
ω_{5BCE} (°)	165.56	236.04	340.41	340.35	336.42
Ω_{5BCE} (°)	248.01	177.79	73.60	73.67	75.41
i_{5BCE} (°)	1.28	0.04	1.05	1.86	1.05
ω_{2000} (°)	154.18	86.21	355.00	348.56	351.09
Ω_{2000} (°)	287.25	355.48	86.88	93.33	88.59
i_{2000} (°)	1.34	0.23	1.03	1.82	1.02
q (au)	0.0201	0.0218	0.0238	0.0264	0.0360
T_q *(Julian date)*	1719779.753	1719780.822	1719781.903	1719783.006	1719784.385

Alternative comet orbits that match the Chinese observations and exhibit the 'going before' and 'stopping over' behaviour of the Jun 8 comet, but with the closest approach to Earth shifted to earlier dates. The orbital parameters are defined on page 395.

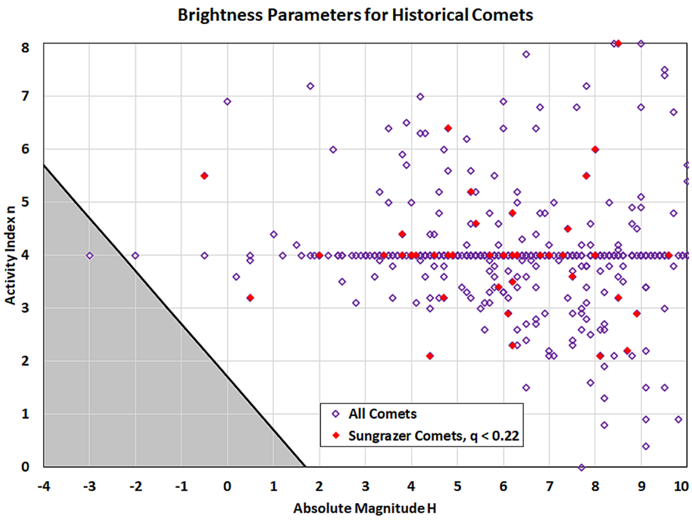

Figure 7. Empirical data from historical comets showing their absolute magnitudes and activity indices. Sungrazing comets (with perihelion distances $q < 0.22$ au) are highlighted. The brightness curves in Figure 9 are represented by the diagonal black line in the lower left of the plot, with the grey shaded area representing comets brighter than this minimal brightness. For the 5 BCE Jun 8 comet's brightness to follow the curves shown in Figure 8, it would have had to be an unusually bright outlier among known comets.

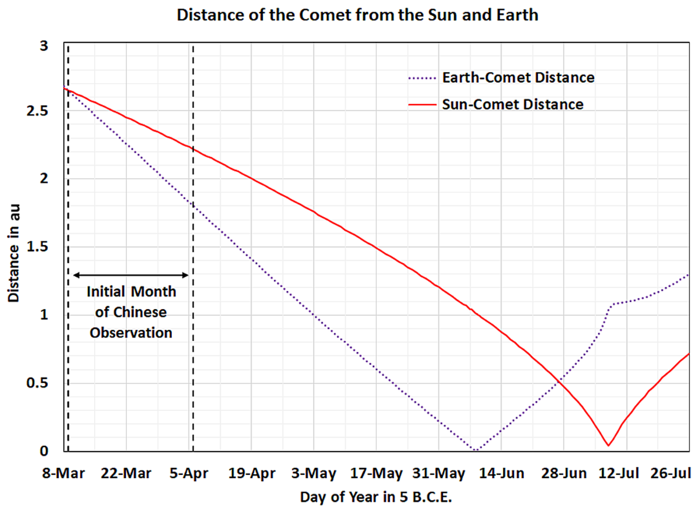

Figure 8. The distance of the Jun 8 comet from Earth and the Sun during 5 BCE. At the time of the Chinese observations, the comet lay 2.0–2.5 au from both the Sun and Earth. Its closest approach to Earth occurred on Jun 8, and perihelion on Jul 8.

based on the hypothetical orbit. From these data, a chart of possible comet magnitudes is shown in Figure 9 for a range of values. The reported H values were calculated to give the required visual magnitude of +3.5 during the early-March visibility window. Figure 7 also includes a shaded region showing values of n and H necessary for the comet to have been visible in early March with a minimum magnitude of at least +3.5, compared with the n and H values of historical comets. Because these H values are much brighter than those of most typical comets, such a bright comet seems very unlikely.

However, many comets show much more complex behaviour, with n and H values changing with various distances from the Sun. In addition, some comets undergo periods of unusual brightening.[86] In some cases, this is associated with fragmentation or splitting of the nucleus. Figure 10 shows a possible magnitude curve where the comet starts with a more typical brightness curve ($n = 2.5$, $H = +4.0$), before undergoing a sudden brightening of about 5 magnitudes starting in mid-March, when it was 2.5 au from the Sun. The brightness then decays exponentially over a few weeks, returning to its 'typical' brightness curve.[87] Allowing for such a temporary brightening event makes it possible that the comet maintained a more representative intrinsic brightness value (H) for the rest of the apparition.

Notably, comet 73P/Schwassmann–Wachmann 3 showed just such a 5-magnitude brightening in H that persisted for many months after its nucleus split near perihelion in 1995.[88] Although comet outbursts are slightly more common after perihelion than before, a 5-magnitude event on the inbound leg at ~2.5 au from the Sun is not unusual.[89,90] Many such variations and permutations are possible that reflect the broad range of historical comet activity. Indeed, Ramsey & Licht (1997) invoked just such an outburst to explain the behaviour of Caesar's Comet of 44 BCE.[91]

As shown in Figures 9 & 10, the comet would have gradually brightened as it approached both the Sun and Earth. Its dimness when first observed in March–April could explain why Herod requested details from the Magi regarding 'the duration of the appearing star', because he and others in Jerusalem would have become aware of it only after it had become quite bright, leaving uncertainty as to when it had first become visible to such trained observers.

On 5 BCE Jun 8, when the comet was closest to Earth, its brightness could have rivalled that of the full Moon (visible magnitude –12.7) and would have been easily visible in daylight. In addition, on that date the comet's motion brought it close to a position between the Earth and Sun, a geometry in which dust in the coma can cause enhanced forward scattering of sunlight. This effect could have temporarily increased the comet's apparent brightness by several magnitudes on the morning of Jun 8.[92]

The unusual brightness of the Jun 8 comet also offers a plausible explanation for a puzzling aspect of the story of the Magi. Despite modern Christmas artistic depictions showing them following the Star at night, travelling after dark was typically avoided in the ancient world.[93] There were no streetlights to illuminate hazards in the road, and travellers risked robbery. It is therefore likely that the Magi travelled by day. A comet bright enough to be visible in the morning sky of Jun 8 as they journeyed toward Bethlehem would have been a most extraordinary sight, and could explain why Matthew says, 'when they saw the star, they rejoiced with exceeding great joy' (2:10).

A few words need to be added regarding the comet's motion and appearance after its close approach to Earth based on its calculated orbit, and why it is not mentioned again in the Chinese annals after the '70 days'. Because of their different longitude, Chinese observers would not have seen the Star 'stop' overhead as in Bethlehem. Instead, from the royal court in Xi'an, the comet would have set a few hours after sunrise on the morning of Jun 8. Around local noon it would have risen again, low in the west, and appeared to pause there until joined by the Sun in the late afternoon, after which they would have set together.

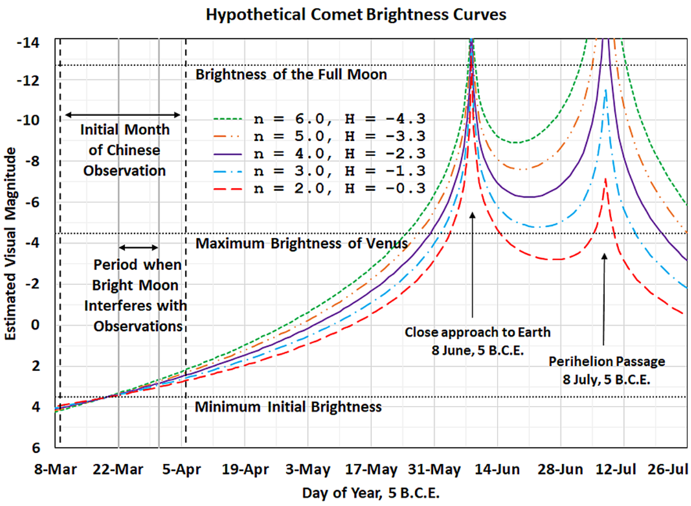

Figure 9. Comet light curves computed using the distances from Figure 8, assuming that the Chinese first observed the Jun 8 comet in 5 BCE Mar, when it was approximately +3.5 magnitude ('Minimum Initial Brightness'). The first appearance is modelled before the bright Moon began to interfere with observations of the dim object in the latter part of March. The comet's brightness rivalled that of the Full Moon at the time of closest approach to Earth.

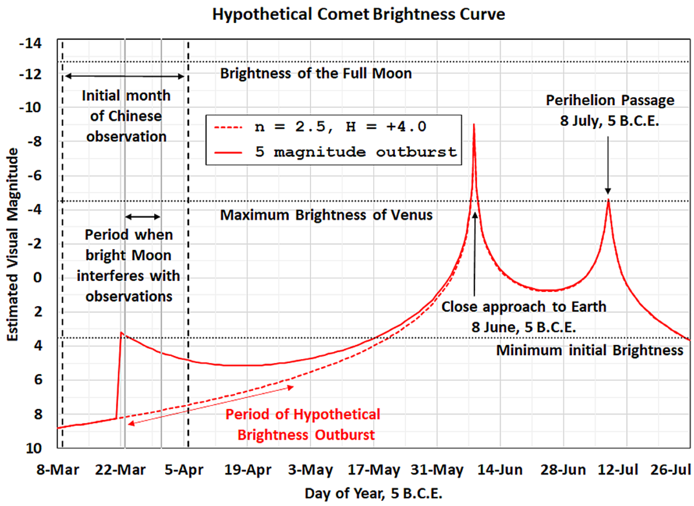

Figure 10. Brightness of the Jun 8 comet based on more typical comet brightness parameters (absolute magnitude +4.0, average activity index 2.5), but in this case including a hypothetical sudden brightening in mid-March. The enhancement, about 5 magnitudes, followed by an exponential decay, is similar to that observed in some historical comets.

After its closest approach to Earth on Jun 8, the comet's orbit would have taken it into a position between Earth and the Sun for several weeks. During the nights immediately following Jun 8, the comet's nucleus would have appeared low in the western sky after sunset, fading each night as it receded from Earth and moved closer to the Sun. It is possible that Chinese astronomers might still have seen the nucleus in the glare of the setting Sun, depending on its brightness. However, the monsoon season usually begins in the Xi'an region by May–June. Modern data indicates that the skies there are cloudy more than half the time during those months, which could have obscured the comet until it had disappeared from view.[94] By mid-June, it would have been lost in the Sun's glare, making further observations impossible. Moreover, the comet's extremely close perihelion passage on 5 BCE Jul 8 could well have resulted in its destruction, preventing any post-perihelion sightings.

Cultural & astrological context for the comet theory

Motivation for the journey to Bethlehem

The subsections herein attempt to answer the following central question: How could a comet appearing in Capricornus in March/April of 5 BCE have convinced the Magi that a king had been born in Judea, prompting them to undertake a long journey? The question may be divided into eight distinct parts: (i) a comet, (ii) in Capricornus, (iii) in March/April of 5 BCE, (iv) Magi, (v) a king, (vi) had been born, (vii) in Judea, (viii) a journey.

There have been many attempts to solve this astrological puzzle. To understand the motivations of these ancient astrologers, it is first necessary to examine how they might have viewed and interpreted celestial phenomena.

Astrological background

Molnar (2013) based his theory of the Star on the discipline of natal astrology, mostly developed during the Hellenistic period and preserved in extant Greek sources, that sought to link astronomical events to the birth of an individual.[95] This method has the benefit of taking the astrological views of the ancient astrologers seriously. However, there is no ancient record of anyone using natal astrology predictively – to foresee a birth. Rather, it was used to cast horoscopes after an individual's birth, to gain insight into that person's nature and destiny. For the ancients, natal astrology used the predictable motions of the Sun, Moon and planets rather than the seemingly erratic appearances and motions of comets. Despite having the attractive attribute of linking astronomical events to a birth (criterion vi), the Magi would not have used horoscopy to interpret the appearance of a comet. Instead, a different branch of astrology must be examined.

Greco-Roman omens

While much Greco-Roman astrological writing is dedicated to the motions of the Sun, Moon and planets, they also mention comets. These references belong to a much broader and ancient tradition of omen interpretation, for which astronomical omens are but a subset.[96] When an omen appeared, a great body of interpretive literature existed to help ancient scholars determine what terrestrial events it might foretell. A major criticism of the comet hypothesis is that ancient astrologers interpreted the omens associated with their appearance as harbingers of evil, rather than as signs of good tidings such as a new king.[97] However, closer examination of comet omens will show that interpretations of comet appearances were not always negative.

Origen, in his *Contra Celsum* (1.59), mentions a writer named Chaeremon the Stoic, who authored a *Treatise on Comets*, no longer extant.[98] It apparently described circumstances in which a comet's appearance could be interpreted as an omen of good, rather than evil. Not much detail is given, but other ancient sources shed more light on positive comet omens. Hephaestion of Thebes, writing in the fifth century CE, wrote on comets and other astrological topics in *Apotelesmatics*, much of it based on older Hellenistic material.[99] He included a bestiary, in which a comet's shape and appearance were used to interpret its meaning. Most comet types were said to foretell evil, but he describes (1.24) a particular kind of comet called 'the Midwife' (Εἰληθυίας, *Eilēthuias*), which signified, among other things, 'a change of matters for the better'. Similarly, Avienius (fourth century CE, quoted in Maurus Servius Honoratus, *Commentary on the Aeneid of Vergil*, 10.272) and Pliny the Elder (first century CE, *Natural History*, 2.23) give examples of situations where comets can have positive interpretations.[100,101]

Mesopotamian omens

Greco-Roman comet omens drew on a much older body of knowledge from Mesopotamia, going back centuries before the Hellenistic era. Catalogues of omens, many astronomical, were preserved in cuneiform tablet archives. In the last few centuries BCE, astrology was undergoing an evolution from the Mesopotamian to the Hellenistic model, including the formalisation of only 12 zodiac constellations and the development of natal astrology. Some astrological developments can be traced in detail, but often the details remain obscure.[102] The Magi, being 'from the east', would likely have been familiar with these cuneiform archives of omen literature.

The largest collection of ancient Mesopotamian omen literature is known as the *Enûma Anu Enlil* (*EAE*).[103] This 'encyclopedia' of approximately 70 tablets lists omens interpreting the appearance of the Moon and Sun, eclipses, earthquakes, and meteorological phenomena such as thunder and rainbows. Many tablets concern omens related to planetary positions within constellations – especially those of Venus and Jupiter. The omens typically forecasted things such as crop yields, commodity prices, weather, wars, disease, and the rise and fall of kings and kingdoms, and they include both positive and negative interpretations. The known *EAE* tablets represent two extant catalogues: one from the seventh century BCE and the other from the third century BCE.[104]

Mesopotamian astronomer/astrologers used several terms to describe comets and meteors, and it is sometimes difficult to ascertain which omens refer specifically to comets.[105,106] However, one word, *ṣallummu*, is known to refer consistently to comets, in Akkadian texts.[107,108,109] This term was used to describe observations of Halley's Comet in the Babylonian *Astronomical Diaries* during its apparitions in 164 and 87 BCE.[110] Some *EAE* tablets include explicit *ṣallummu* omens.

One difficulty in reconstructing Mesopotamian comet interpretations is that many cuneiform tablets are fragmentary or incomplete. This is illustrated by the text of tablet K.3099 from the British Museum, itself an example of *EAE* 52.[111] There are at least six (and possibly more) previously unpublished *ṣallummu* omens on this tablet's reverse, but only four are preserved completely enough to determine their meaning. While most of the preserved comet omens on this tablet have negative interpretations, one (K.3099, lines 6′–7′) is positive, and can be reconstructed using two other fragmentary tablets, K.3524 (lines 4–6) and Rm.100 (lines 1′–2′).[112,113] The unpublished text was kindly assembled and translated for this paper by M. Schreiber (pers. comm.):[114]

> DIŠ *ṣal-lum-mu-ú* $^{\text{mul}}$UGA$^{\text{mušen}}$ IGI.DU$_8$ *ina* KUR DÙ.A.BI $^{\text{munus}}$PEŠ$_4$-MEŠ […] ⸢SILIM$^?$⸣-MEŠ MÁŠ.ANŠE Ù.TU SI.SÁ KU$_6$ ina I$_7$ *e-ru-ta*$_5$ ŠUB MUŠEN ina AN-e NUNUZ ú-šal-lam
>
> 'If a *ṣallummu* appears in the Raven-star, in the entire land pregnant women [will bring their foetuses] to term, the cattle will give birth easily, the fish in the river will spawn, the bird in the sky will hatch eggs.'

The Raven-star $^{\text{mul}}$UGA$^{\text{mušen}}$ corresponds to the constellation Corvus.[115] While this omen does not have any obvious link to the Chinese observations of a comet in Capricornus – as Corvus lies far from that region of the sky – it demonstrates that Mesopotamian comet omens, like those of the Greco-Roman world, were not uniformly negative. Under certain circumstances, they could have distinctly positive interpretations.

A number of Mesopotamian comet omens remain unpublished or untranslated. Further research in this area could help shed light on how the Magi might have interpreted a comet's appearance, and how cometary omens evolved from Mesopotamian omen literature into that of Hellenistic and Roman astrologers.[116]

Another intriguing tablet that may shed light on comet omens is *EAE* 56, originally translated and described by Largement (1957).[117,118,119] Unlike many of the *EAE* tablets that describe omens for specific objects, *EAE* 56 gives a list of omens for a generic type of astronomical object known in Akkadian as a *bibbu* (Sumerian $^{\text{mul}}$UDU.IDIM). The etymology of *bibbu* appears to refer to a 'wild goat', and was applied to a variety of astronomical objects that seemed to move or wander among the background stars – much as the Greek word for planet (πλανήτης, *planētēs*) meant 'wanderer'.[120]

It is clear from the omens in *EAE* 56 that these *bibbu* could sometimes refer to the conventional visible planets or even meteors, but the category also appears to have included comets. This can be inferred from the descriptions in the tablet: a *bibbu* could remain visible for multiple nights (unlike a meteor) and could move far from the ecliptic plane, even near the north celestial pole (which a planet cannot do). Indeed, Largement (1957) refers to a comet as 'the *bibbu* par excellence'.[121] While Chadwick (1993) casts doubt that such *bibbu* omens could refer to a comet,[122] the wide variety of omens described in *EAE* 56 makes a cometary interpretation plausible, at least in some cases.

While many of the *bibbu* omens listed in *EAE* 56 had negative interpretations, many were associated with positive ones. One example is particularly relevant (lines 35–36 in Largement's nomenclature):

> $^{\text{mul}}$UDU.IDIM ana $^{\text{mul}}$UDU.IDIM TE DUMU LUGAL ša ina IRI ZA$_3$-ia$_5$ aš$_2$-bu ana AD-šu$_2$ ḪI.GAR DU$_3$$^{\text{uš}}$-ma AŠ.TE la$_3$ DAB$^{\text{bat}}$ DUMU ma-am-ma-an-ma
>
> '(If) a *bibbu* approaches (another) *bibbu*: the son of a king who lives in a town on my border will make rebellion against his father but will not seize the throne; the son of a nobody will emerge and seize the throne; he will return the gods' temples to their (former) condition; he will establish regular offerings for the great gods; he will provision the temples equally.'[123]

This omen contains several noteworthy features. If *bibbu* in this context can be interpreted as a comet, it would represent another positive comet omen. In addition, it is an omen about events in the borderlands. While not explicit, this omen might have been interpreted as referring to possible changes in the royal dynasty of one of the client kingdoms that existed around the periphery of the Parthian Empire. Whether or not this was the actual omen used by the Magi, it nonetheless demonstrates that positive omens could possibly: (i) refer to comets; (iv) have been familiar to the Magi; and (v) refer to changes in a royal dynasty (vii) in a client border kingdom.

Astrological geography & the Magi's trip to Judea

Another aspect of ancient astrology is known as astrological geography, in which the location of an astronomical omen among the stars was mapped to a particular geographic area. The method by which each zodiac constellation was assigned to a particular country or region has been extensively studied by Steele (2015) and Heilen (2015).[124,125] They show the clear evolution of the Hellenistic version directly from earlier Mesopotamian omen traditions preserved in cuneiform tablets. The best-known version of this Greek astrological map was outlined by Claudius Ptolemy in his *Apotelesmatika* (also known as the *Tetrabiblos*),[126] in which he associates Aries with the region of Judea, among other regions. Molnar (2015) uses this association as a central part of his thesis to identify lunar and planetary phenomena in Aries that may have had astrological meaning for the Magi, indicating a new king had been born in Judea.[127]

However, Heilen (2015) has shown that Ptolemy's 'map' was from a relatively late date (second century CE), and that the earliest stratum – dated to several centuries BCE – of the development of Hellenistic astrological geography was likely preserved by Paul of Alexandria (*Introduction*) and others.[128] In this earlier system, Judea is not specifically mentioned, but Syria is, and Syria is associated with Capricornus, not Aries. The geographer Strabo (*Geographica* 6.2), writing near the time of Jesus' birth, explicitly included Judea within the geographic region of Syria.[129] If the Magi were using this early astrological geography map and interpreted a comet appearing in Capricornus as pointing to a royal birth in the region of Syria, the northern sub-region defined as the Roman province of Syria would not have been the obvious location to look. It had been a province since 64 BCE and no longer had a royal dynasty. However, the kingdom and royal dynasty of Judea, consisting of the southern portion of the geographic region of Syria, would have been a logical alternative.

In addition to this direct geographic link to Judea-Syria, de Jong (2015) and van Kooten (2015) have shown that during this period, the Parthians took a keen interest in the royal dynasties of the client kingdoms between Parthian and Roman territory.[130,131] The Magi, with their reputation for legitimising royal persons, may have played a key role in gathering intelligence among these client kingdoms to monitor any changes in the royal dynasties' status. van Kooten (2015) details the history of the Romans and Parthians during this period, and despite several bitter wars fought between them in the first century BCE, Emperor Augustus established peace with the Parthian ruler Phraates IV in 20 BCE.[132] Between then and the Parthian king's death in 2 BCE, relations between the two powers were better perhaps than they had ever been or would ever be. This contrasts with the strained Rome-Parthia relations of the latter first century CE, when Matthew was likely written. This context helps explain why an astronomical event (ii) in Capricornus (iii) in 5 BCE could plausibly have influenced (iv) the Magi to (viii) make a journey (vii) to Judea.

The most elusive link has been to point (vi): finding an omen in the ancient astral literature that indicated the birth of a king. Origen (*Contra Celsum* 1.59) reports that some believed the appearance of a comet could herald the commencement of a new dynasty.[133] Panaino (2018) explored the extant literature in an attempt to locate an explicit omen linking the birth of a king to the appearance of the comet that Pompeius Trogus in his *Philippic Histories* (preserved by Justinus in his *Epitomae* 37, 2, 1–3) said marked the birth of Mithridates VI Eupator of Pontus in 120 BCE.[134] Ultimately, Panaino (2018) was unable to identify any obvious omens that could directly point to the birth of a king.[135] Nevertheless, Trogus preserves a definitive report that some astrologers believed the comet marked the birth of the king of Pontus, even if the specific omen can no longer be identified. Plutarch mentions another royal birth omen in his *Life of Alexander* (3.4), this one with direct links to the Magi.[136] He says that when Alexander was born, the Magi in Ephesus interpreted the fire that destroyed the temple of Ephesian Artemis as an indicator that a 'great calamity for Asia had that day been born'. Even if it is impossible to identify the exact omens – astral or otherwise – that point to (vi) the birth (v) of a king, such omens clearly existed and would have been familiar to the Magi, potentially including some that associated a comet with a king's birth.

While we cannot connect all the dots in the corpus of omen literature available to the Magi that directly link the 5 BCE Jun 8 comet to a royal birth in Judea, sufficient links exist to support a plausible scenario. The body of knowledge accessible to the Magi seems to have included all the necessary pieces of the puzzle, even if the complete picture cannot be fully assembled.

Other astronomical events

In addition to the comet described in the Chinese chronicles and discussed in this paper, several other noteworthy astronomical events occurred around that time that may – or may not – have held significance for the Magi observing the Middle Eastern skies. Beyond the various planetary motions and conjunctions in 7 and 6 BCE often proposed as candidates for the Star of Bethlehem, other intriguing events occurred closer in time to the appearance of the 5 BCE comet.[137] The Chinese records discuss two such objects that may have held significance for the Magi.

The 'white vapour' observation in early 5 BCE

The first object appeared a few weeks earlier in 5 BCE, recorded in the *Han Shu: Tianwen Zhi*, chapter 26:

> '1st year of the *Chien-p'ing* reign period of Emperor Ai of the Han Dynasty, 12th month: a white vapor emerged in the southwest, reaching from the ground up to the sky. It emerged beneath *Shên* and penetrated *T'ien Tz'ū*, as wide as a bolt of cloth and over 10 *zhang* long. It lasted more than 10 days before departing.'

The month described corresponds to the period from 5 BCE Jan 10 to Feb 7, just a few weeks before the appearance of the 'broom star' described in this paper. *Shên* corresponds to the constellation Orion, and *T'ien Tz'ū* to the constellation Lepus, just south of Orion. A length of 10 *zhang* indicates an object stretching approximately 100° across the sky. Hasegawa & Nakano (2001) argued that this description, and others like it in the Chinese records, may represent observations of sungrazer comets, and they constructed a plausible sungrazer orbit for this comet in early 5 BCE.[138] Although the appearance of another comet just a few weeks before the March–April 'broom star' would have been most unusual, the orbit they propose could not have been the object later visible in Capricornus.

The 'fuzzy star' observation in 4 BCE

In addition to these two observations in 5 BCE, the Chinese recorded another object in *Han Shu: Ai di ji*, Chapter 11:

> '3rd year of the *Chien p'ing* reign period of the Emperor Ai of the Han Dynasty, 3rd month, day *jiyou*; there was a fuzzy star [*po hsing*] in *Ho Ku.*'

The date of this observation is 4 BCE Apr 24. The term *po hsing* ('fuzzy star') typically refers to a comet with no distinct tail, or one with short rays extending in all directions,[139] though it could also describe a nova or other odd stellar appearance.[140] There is another record of a comet at this time in the Korean annals, but it appears to be a copy of this earlier Chinese record with a corrupted date,[141] *contra* Clark *et al.* (1977).[142]

Ho Ku corresponds to the constellation centered on Altair (α Aquilae), not far from the region of the sky where the previous year's comet appeared (see Figure 2). This constellation is often associated with the Lunar Mansion of *Ch'ien Niu*. It is surprising that a comet should appear in roughly the same region of the sky, almost exactly one year after the 5 BCE event. It is possible that this entry refers to the same 5 BCE comet, misdated by one year, in which case this observation might assist in refining its orbit. However, since the Chinese record describes only a single observation of an ambiguous object, it is more prudent to assume this was an unrelated comet or other astronomical event.[143]

Other influences on Magian interpretation

In addition to astronomical phenomena, there is no way of determining if meteorological events – which also formed part of ancient omen literature – may have influenced the Magi's interpretations, simply because such information has been lost to time. Likewise, the importance of oneiromancy in Magian mysticism means that dreams, too, cannot be discounted as a possible influence on their astrological reasoning.

The silence of other historical sources concerning the 5 BCE comet

An unusually bright 'great comet' making a close approach to Earth, such as the Jun 8 comet, might be expected to appear in multiple historical accounts; however, there are no apparent Greco-Roman records of any comet in 5 BCE. A closer look at the available evidence might help explain this omission.

Our best extant sources for the life of Herod the Great are the works by Jewish historian Flavius Josephus: *Antiquities of the Jews* and *The Jewish War*.[144] His multiple references to the dates of Herod's reign in relation to events in the wider Roman world clearly establish Herod's death in 4 BCE (according to most scholars), and consequently help us date Jesus' birth. While Josephus lived later in the first century CE and was not an eyewitness to Herod's life, he probably drew much of his information from the historian Nicolaus of Damascus, an intimate friend of Herod whose works are now mostly lost.[145] Josephus rarely reports on astronomical events. For instance, he reports only one eclipse in all his voluminous works – the lunar eclipse around the time of Herod's death, possibly that of 4 BCE Mar (*Antiquities of the Jews*, 17.6.4).[146] He also mentions a comet preceding the destruction of Jerusalem, that he likely witnessed, which may refer to the 66 CE appearance of Halley's Comet.[147] However, he omits any mention of its bright appearance in 12 BCE,[148] nor the famous comet of 44 BCE associated with Julius Caesar's death.[149] Perhaps his source, Nicolaus of Damascus, simply did not consider comets noteworthy. Indeed, the extant fragments of Nicolaus' *Life of Augustus* contain no astronomical events at all, including the comet of 44 BCE.[150]

Another detailed history of this period is by the Roman historian Cassius Dio.[151] He lived in the second and third centuries CE, but compiled a history of Rome going back to its founding. Much of it survives, and he shows an interest in astronomical omens. In Book 54 of his Roman History, Dio records a comet in 12 BCE, which he associates with the death of Marcus Agrippa, and this is thought to be the only Greco-Roman record of Halley's Comet in that year.[152] In Book 55, Dio would have covered the events at the time of Jesus' birth, but the extant copies contain a lacuna:[153] the manuscripts break off just as he begins to describe the events of 5 BCE, resuming only at 2 BCE. If Dio did mention the comet of 5 BCE, that record is unfortunately lost.

Amongst a listing of historical comets, Yeomans (1991) mentions 15 probable Chinese comet observations in the first century BCE.[154] Of these, only the 44 BCE comet and Halley's Comet (in 87 BCE and possibly in 12 BCE) appear in Greco-Roman sources. This illustrates how incompletely classical records preserve astronomical observations in this period.

In general, the history of Augustus' reign during Tiberius' so-called 'retirement' to Rhodes, roughly from 6 BCE to 2 CE, remains obscure due to a lack of records of sufficient quality. Consequently, knowledge of Roman history during this interval is notoriously incomplete.

There is one other category of ancient source that includes comet observations. In addition to compiling omen tablets to explain astronomical events, the Mesopotamian astronomer/astrologers kept detailed *Astronomical Diaries* – records of celestial events extending back many centuries.[155,156] These include historical observations of Halley's Comet in 164 and 87 BCE.[157] However, the extant corpus of *Astronomical Diaries* inexplicably ends after 61 BCE. It is unclear whether the astronomers suddenly stopped recording observations, changed to less durable writing media such as papyrus, or whether later records simply remain undiscovered. If records from this later period were ever found, they could provide precise positions and dates to refine the 5 BCE comet's orbit.

The age of children during the 'slaughter of the innocents'

The only chronological information in Matthew concerning the Star's duration comes from the story of Herod's 'slaughter of the innocents'. Matthew 2:16 says that Herod ordered the execution of all the male children (πάντας τοὺς παῖδας, *pantas tous paidas*) 'two years old and younger' (ἀπὸ διετοῦς καὶ κατωτέρω, *apo dietous kai katōterō*).[158,159] Herod chose this age range 'according to the time (κατὰ τὸν χρόνον, *kata ton chronon*) which he had diligently enquired of the wise men' (2:16), indicating he was trying to determine a possible date range for the child's birth.

At first glance, this information seems to contradict the theory proposed in this paper – that the comet appeared in 5 BCE Mar, and that the Magi arrived in Bethlehem in early June, after no more than three months. However, an alternative interpretation may be suggested by practices in Far Eastern cultures. Traditionally, in regions such as China and Korea, a child was regarded as 'one year old' at birth, and then aged a further year at the next New Year's Day. Known as 'East Asian age reckoning' or 'Korean age', this system meant that a child born late in the year could be considered 'two years old' soon after birth.[160]

Evidence that a similar system was used in the ancient Near East comes from papyri discoveries in Roman Egypt.[161] Kruit (1998) has shown that, under certain circumstances, a child described in papyri as 'one year old' meant 'born in the current year'. In this reckoning, the age incremented at the beginning of the new year, much as it did in Far Eastern cultures: 'The fact whether or not a child already had celebrated his birthday is irrelevant. What matters is the age of the child in the year of registration, i.e., the age a child already has attained or will attain in the current year.'[162] The use of the system in two geographically distant cultures suggests it may have been more widespread than previously recognised.

If such a system were in use in Judea in the late first century BCE, Herod's command might have meant: 'kill all the male children born during this year or the previous one'. If so, the date of the new year in 5 BCE becomes significant for understanding Herod's estimate of the new king's age. A lunar calendar was in use in Judea, and – unlike the modern systematic Jewish calendrical system developed in the fourth century CE – during this period the assigning of 'leap months' was decided by the timing of natural agricultural events.[163] Generally, the first month (*Nisan*) was chosen so that its midpoint (the 14th day) coincided with the Full Moon nearest the vernal equinox. In 5 BCE, the equinox fell on the night of Mar 22/23, and the Full Moon followed on Mar 23/24 – the night of a lunar eclipse visible from Judea. Without more information, it is difficult to determine if the Sanhedrin, who determined the calendar, began *Nisan* in early March or early April that year. Fortunately, the Babylonian calendar, reassembled from cuneiform tablets, provides a helpful parallel.[164] While not identical to the Judean calendar, the standardised Babylonian calendar used a similar system, and the Judean agricultural calendar was likely often aligned to the Babylonian. According to modern Jewish calendrical calculations,[165] the first day of *Nisan* in 5 BCE corresponds to Mar 9. Using the Babylonian calendar, the final month of the previous year (*Addāru* – equivalent to the Judean *Adar*) ran from Mar 10–Apr 7, and the first month of the new year (*Nīsannu* – equivalent to *Nisan*) began on Apr 8.[166] Therefore, the lunar month in which the Chinese reported the appearance of the comet corresponds to the last lunar month of the previous year in the Babylonian calendar. When Herod enquired of the Magi when they had first observed the Star, the month they named would have been that final month of the previous year according to their Babylonian – and possibly also Judean – calendar.

It remains uncertain whether this 'Egyptian/East Asian age reckoning' system was used in Judea at this time, and if so, which date marked the new year for incrementing a child's age. Nevertheless, this information presents an intriguing possibility that may help reconcile the chronological clues in the story of the 'slaughter of the innocents' with the timing of the Chinese comet observations.[167]

Conclusion

This paper has addressed a simple question: is there an astronomical event that can explain the detailed description of the Star of Bethlehem in Matthew? A comet candidate has been presented that can explain all aspects of Matthew's pericope.

Chinese records describe a comet visible for more than 70 days in the constellation Capricornus in 5 BCE Mar/Apr – a plausible date for the Star of Bethlehem. A comet orbit can be constructed that both fits the Chinese observations and passed very close to Earth in early June. On one particular June day, this comet could have moved in such a way as to appear to 'go before' someone travelling from Jerusalem to Bethlehem and then 'stop' nearly overhead for about two hours. This unusual comet motion would have occurred during daylight, when ancient people would normally travel.

Egyptian papyri indicate that, during this period in the ancient Near East, the phrase 'two years old and younger' sometimes meant 'born this year or last year', suggesting that Herod's order reflected the timeframe the Magi reported for the comet's first appearance. Initially, the comet would have been quite dim, likely noticed only by the trained Magi astronomers. Herod's question regarding when the Star first appeared may therefore indicate that he only became aware of its existence once it had brightened sufficiently to be unmistakable, and some weeks after its observation by the Magi.

Mesopotamian cuneiform omen tablets indicate that comets could be considered positive omens under certain circumstances, and some omens could have been interpreted to link a comet's appearance with events in the royal families of client kingdoms along the Parthian border. At the same time, a school of astrological geography associated astronomical events in Capricornus with the region of Syria, including the kingdom of Judea, which may have influenced the Magi's belief in the birth of a new Judean king. Furthermore, the political climate made a journey by the Magi to the Roman client kingdom of Judea possible. While it is only possible to reconstruct a partial picture of the astrological meanings of such a comet, the candidate presented here corresponds to all aspects of both the Chinese observations and the descriptions of the Star in Matthew.

In conclusion, although it is impossible to assert with certainty that this comet was definitely the Star the Magi saw, this study shows that it is no longer justifiable to claim that 'no astronomical event' could possibly have behaved in the manner described by Matthew.

Acknowledgments

This paper is dedicated to the memory of my mother, Jean Matney, who always loved the Star of Bethlehem planetarium show, and to the memory of my first boss, Don Garland, director of the Noble Planetarium, who would have loved putting this theory on the big dome.

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