Crossing Geographical Borders from Minoan Crete

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We present the evidence that the Minoans possessed in the Early Bronze Age the two prerequisites for overseas travel, sea-worthy sailing boats and skill in stellar navigation. It consists of representations of sailing boats and indications of contemporary systematic observations of the sun, moon and stars, which would have been necessary for accumulation of the knowledge needed for stellar navigation. We also studied Greek texts for traces of such navigation in the Bronze Age. The most relevant text is Aratos' Phainomena. *A problem here has been the fact that some of the poet's stellar positions are incorrect for his time, which has led to the questioning of his work as a useful source. His errors can be explained, however, on the assumption that the* Phainomena *belonged to a didactic tradition of navigational lore which had its origins in the Bronze Age. We present statistical analyses of astronomical data in the poem which indicate that this is the case. We argue also that the developments on Crete were indigenous and not initiated from abroad.*

Introduction

Crossing the borders of Crete in the Bronze Age meant, of course, seafaring and according to the archaeological evidence the Minoans were plying the waters of the Aegean already in the Early Bronze Age. Metals from Attika and the Cyclades and obsidian from Melos, for example, were reaching Crete at that early date.[1] We present the archaeological and textual evidence that the Minoans possessed at that time the two prerequisites for these overseas contacts, sea-worthy sailing boats and the art of stellar navigation.

Sailing boats

The possession of suitable sailing boats is attested by the many representations of such vessels on sealstones from Early Minoan III (ca 2200-2000 BCE).[2] Since there were no navigable rivers in Crete, these boats can only have been intended for sailing in the Mediterranean.

There is no clear source of foreign influence on the development of the Minoan sailing boat. Claims of Cycladic priority are speculative and not supported by archaeological evidence. Early Egyptian ships were developed for the far safer waters of the Nile. They were neither intended nor suitable for sailing on the open sea. Their combination of large sails and shallow hulls bear witness to this. The first sailing ships used by the Egyptians for seafaring were simply their river boats, which they strengthened lengthwise with trusses.[3] Therefore the Egyptians were not likely to have influenced the Minoans in the construction of seagoing vessels. There was Bronze Age sailing in the Near East and Mesopotamia, but we know little about the types of boats used in those areas before the Late Bronze Age. However, there is no evidence that they influenced Minoan development.

We have, in fact, no firm evidence for earlier, more technically accomplished seafaring ability than the Minoan in the Mediterranean. The frescoes from Thera give us a good picture of the capabilities of Minoan sailing ships at the height of their development.[4] Whether the boats were Cycladic or Minoan has no relevance since technical achievement in the two areas, regardless of their political relationship, was likely to have been on a par by the Late Bronze Age. Typical for these vessels are a mast in the center and a small sail in relation to boat size. These features contribute to stability and maneuverability, permitting quick adjustment for the changing winds and sudden squalls for which the Aegean is feared still today.

Stellar navigation

The other prerequisite for Minoan seafaring would have been skill in stellar navigation as there was no alternative available at the time. The notion of island-hopping and finding the way by following coastlines has entered the literature, but this was an unrealistic method for some of the destinations from Crete, such as Egypt and Thera. These places could not be reached in a day's sailing and there were no islands in between. Moreover, the Aegean islands are mountainous and the winds near their shores are treacherous. Following their coasts would have been dangerous because of the risk of sudden squalls.[5] If stellar navigation were a possibility it would have been the method of choice. The prevailing winds in the eastern Mediterranean in the summer have often been assumed to have necessitated a west-to-east course. The evidence, however, gives witness to the surprising capabilities of experienced seamen for sailing close enough to the wind, even in boats with difficult-to-handle sails.[6] Increasing skill in sailing towards the wind and the development of navigational methods for traveling out over the open sea are likely to have been mutually re-enforcing.

The most persuasive argument that the Minoans independently developed stellar navigation comes from the evidence in Crete for systematic study of the celestial bodies no later than Early Minoan III. From our archaeoastronomical investigations of the orientations of important monuments, we can infer a beginning for this observational astronomy before that early date. So far we have measured 14 buildings and they all show orientations to significant celestial events.[7] The majority are to sunrise or sunset at the solstices or equinoxes, which means that chance can be ruled out as a factor.[8] There were observation traditions also in Egypt and Mesopotamia, but they seem different in their aims, as they do not show the same focus on the solstices. The earliest Minoan orientation seems to be that of the monumental building under the west wing of the palace at Knossos, which dates to Early Minoan III.[9] It had the same orientation as the later palace, which is oriented to the point of sunrise at the equinoxes above the Ailias Ridge. The orientation implies, of course, systematic astronomical observations from an even earlier date.

The astronomical knowledge acquired by the Minoans through their observations would have been useful not only for maintaining a calendar, as we have argued elsewhere,[10] but also of course for navigation. The orientations of their important buildings to sunrise and sunset at the equinoxes and solstices are likely to have had as consequence good acquaintance with the stars which rose and set in the same directions. By relying on such a series of stars or constellations with the same angular distance from the Equator, the declination, a fixed direction can be maintained by a pilot if he steers sighting upon them as they appear low on the horizon, either when rising in the east or when setting in the west.

The Greek texts

We have further evidence for Bronze Age stellar navigation in Greek literature. The earliest passage tells of Odysseus' use of the Pleiades, Bootes and the Great Bear to find his way home from Calypso's island.[11] Although these lines were written early in the Archaic Period, the author was relating the heroic sagas from the Mycenaean culture of several centuries earlier. It is certain that he had accurate knowledge of Mycenaean armor and similar data since a number of his descriptive details agree with objects recovered from Mycenaean graves.[12] The question is whether or not his account of stellar navigation can be referred back to the Bronze Age. We hope to show that it is part of a tradition which is no later than the beginning of the Middle Bronze Age.

There are a number of texts from the category of didactic poetry, the purpose of which was to present in easily remembered verse practical information for farmers and sailors. They told how natural signs, including the positions of the stars, could be used to tell the time of the year, the time to sow, to harvest, to venture out to sea and so on. The stellar positions used for these purposes were the first morning and evening risings and settings of bright stars and constellations. A popular poem of this type throughout antiquity was Aratos' *Phainomena*, which was intended primarily for sailors. It has detailed descriptions of the horizon positions of the stars relative to each other and to the great circles (North Pole, Arctic Circle, Celestial Equator, Tropics of Cancer and Capricorn, and Ecliptic), the kind of information which is essential for stellar navigation.

Aratos' *Phainomena* was composed in ca 275 BCE and is the verse rendition of a work with the same title by the astronomer Eudoxos, written about 75 years earlier.[13] Hipparchos, in his detailed commentary written ca 150 BCE on the two books, makes it clear that Aratos on the whole is faithful to the Eudoxian original, which exists today only in fragments.[14] Both Aratos and Eudoxos gave positions that are faulty by several degrees for many stars. We can discount copying errors in the manuscripts as an explanation since Hipparchos repeats the wrong positions in his commentary and they were still to be found in the several translations of Aratos by Roman authors, including Cicero and Germanicus Caesar. The mistakes were a mystery to Hipparchos since Eudoxos was a great astronomer and should have been able to give stellar positions correct to about a fifth of a degree. It was probably Hipparchos' reflection over these errors that later led him to the discovery of precession, which is the slow change in the positions of the stars relative to the earth, a change equal to about 1.4° per century.

It has been argued that the information in the *Phainomena* was indeed correct, but not for Athens in the 4th century. It was valid instead for Crete in the Bronze Age,[15] the errors being due to failure to correct for precession, which was unknown. There are passages in Aratos' text that support an origin in Bronze Age Crete: for example, he gives Minoan sources for the names for the two Bears and the Crown of Ariadne.[16] Arguments for an earlier date, however, were dismissed by Dicks for two reasons: 1) the errors are not consistent, as we would expect if they were based on data compiled at the same time and 2) the information given by Aratos and Eudoxos presupposes the system of celestial spheres for which Eudoxos is given credit.[17]

We decided to test the hypothesis of derivation from an earlier tradition by calculating the positions of the stars that Aratos and Eudoxos placed near or on the Celestial Equator and the Tropics of Cancer and Capricorn from 3250 BCE. These are the theoretical circles which are defined by the points on the horizon where the sun rises and sets at one of the solstices or at the equinoxes (six points in all). We need not consider it necessary to assume that the Minoans had developed a system of celestial spheres of the type created by the Greeks. The Minoans could simply have selected the stars which rose or set near the six points. This is supported by our investigations in Crete as we have found these positions marked by the orientations of several Minoan structures that date to the beginning of the Middle Bronze Age.[18] We assumed that the lack of consistency in the errors in the texts was due to the replacement through the years of stars which had moved from their original positions because of precession by others which had come closer. We were interested to see if this would be verified in our results. To our knowledge calculations based on the individual stars through time have not been made earlier in order to solve this problem. Such computations would, of course, have been extremely laborious and time-consuming before the modern computer.

We had first to identify the individual stars and to do so we relied on the text of Aratos, Hipparchos' commentary, Ptolemy's star catalogue and a modern stellar atlas.[19] Some of the stars are given by both Aratos and Eudoxos, others only by Aratos or only by Eudoxos (Table 1). Examples of the kind of information given are:

> *Aratos on the Tropic of Cancer* (*Phainomena* 481-484):
> On it are carried both heads of the Twins, and on it lie the knees of the firm Charioteer, and after him the left lower leg and the left shoulder of Perseus.
> *Eudoxos on the Tropic of Cancer*, (from Hipparchos I.2.18):
> The middle parts of the Crab are on it and the middle parts lengthwise through the body of the Lion, and of the Maiden a small part is above, and the neck of the neighboring Serpent, and the right hand of Hercules.

We could identify rather securely the stars in the table marked with an asterisk. The heads of the Twins, for example, are without doubt α and β Gemini whereas the knees of Auriga are somewhat uncertain and the stars meant for Virgo are impossible to identify as they are so vaguely specified. We identified a total of 111 stars.

We then calculated the deviation for each of these stars from the respective rising and setting points at intervals of 250 years from 3250 BCE to the year zero and constructed tables like Table 2 for deviations from $\pm 1°$ to $\pm 5°$. We found that, although the number of stars in each deviation interval increased as we increased the size of the interval, the proportions remained about the same. We found the interval of $\pm 2½°$ to be a good working value (Table 2). It is the interval which can be measured approximately by the width of a man's thumb held up at arm's length for sighting. The table shows when a star is within this interval and for how long. For example, α Lep came within 2½° of the rising and setting points of the sun at the winter solstice sometime between 1750 and 1500 BCE and remained there until sometime after

circle and *bright star* **number**[1]	**name and brightness**	**from Aratos**	**from Eudoxos (via Hipparchos)**
Tropic of Cancer: 2891	α Gem 2	Heads Gem*	Heads Gem*
2990	*β Gem 2*	*Heads Gem**	*Heads Gem**
1843	χ Aur 5	Knees Aur	Knees Aur
799	θ Per 4	L shoulder Per*	L shoulder Per*
1228	ξ Per 4	L shin Per*	L shin Per*
8965	ι And 4		R. hand And*
8976	κ And 4		R. hand And*
8961	λ And 4		R. hand And*
469	χ And 5		Between feet And
82	ρ And 5	mid R upper arm And*	
8454	π Peg >4	Hoof Peg*	Feet Peg*
8315	κ Peg >4	Hoof Peg*	Feet Peg*
7478	φ Cyg 5	Head Cyg*	
7615	η Cyg >4	Neck Cyg*	Neck Cyg*
7949	ε Cyg 3		L. wing Cyg*
6603	*β Oph>4*	*Shoulders Oph**	
6629	γ Oph 4	Shoulders Oph*	
6281	ι Oph 4	Shoulders Oph*	
6299	κ Oph 4	Shoulders Oph*	
6556	α Oph >3		Head Oph*
6117	ω Her 5		R hand Her
5788	δ Ser 3		Neck Ser*
5867	β Ser 3		Neck Ser*
5868	λ Ser 4		Neck Ser*
5854	α Ser 3		Neck Ser*
5892	ε Ser 3		Neck Ser*
3982	α Leo 1	Beneath breast Leo*	Middle parts Leo*
3980	31 Leo 4	Beneath breast Leo*	Middle parts Leo*
3937	ν Leo 5	Beneath breast Leo*	Middle parts Leo*
3975	*η Leo 3*	*Beneath breast Leo**	*Middle parts Leo**
4133	ρ Leo 4	Beneath breast Leo*	Middle parts Leo*
4227	53 Leo 6	Beneath belly Leo*	Middle parts Leo*
4399	ι Leo 3	Genitals Leo*	Middle parts Leo*
3366	η Cnc <4	N eye Cnc*	Middle Cnc *
3357	θ Cnc <4	S eye Cnc*	Middle Cnc*
3449	γ Cnc >4	N nebula Cnc*	Middle Cnc*
3461	δ Cnc >4	S nebula Cnc*	Middle Cnc*
Celestial Equator: 617	α Ari >3	Lengthwise parts Ari*	Middle parts Ari*
553	β Ari 3	Lengthwise parts Ari*	Middle parts Ari*
646	η Ari 5	Lengthwise parts Ari*	Middle parts Ari*
669	θ Ari 5	Lengthwise parts Ari*	Middle parts Ari*
773	ν Ari 6	Lengthwise parts Ari*	Middle parts Ari*
888	ε Ari 5	Lengthwise parts Ari*	Middle parts Ari*

	1320	μ Tau 4	Knees Tau*	
	1473	90 Tau 4	Knees Tau*	
	1852	δ Ori 2	Belt Ori*	
	1903	ε Ori 2	Belt Ori*	
	1948	ζ Ori 2	Belt Ori*	
	3845	ι Hya 4	Turning Hya*	
	4343	β Crt >4	Crt*	
	4287	α Crt 4	Crt*	
	4405	γ Crt 4	Crt*	
	4382	δ Crt 4	Crt*	
	4623	α Crv 3	Crv*	
	4696	ζ Crv 5	Crv*	
	4786	β Crv 3	Crv*	
	4630	ε Crv 3	Crv*	
	5652	ι Lib 4	Lib	Middle part Lib*
	5787	γ Lib 4	Lib	Middle part Lib*
	6378	η Oph 3	Knees Oph*	
	6175	ζ Oph 3	Knees Oph*	
	7525	γ Aql 3	Not much of Aql	L. wing Aql
	8413	ν Peg 4	Head Peg*	
	8450	θ Peg 3	Head Peg*	
	8634	ζ Peg 3	Neck Peg*	
	8665	ξ Peg 4	Neck Peg*	
	39	γ Peg <2		Lower back Peg*
	352	τ Psc 5		Northernmost Fish*
	383	υ Psc 4		Northernmost Fish*
	360	φ Psc 4		Northernmost Fish*
	351	χ Psc 4		Northernmost Fish*
	310	ψ1 Psc 4		Northernmost Fish*
	328	ψ2 Psc 4		Northernmost Fish*
	339	ψ3 Psc 4		Northernmost Fish*
Tropic of Capricorn:	8127	φ Cap 5	Middle Cap*	Middle Cap*
	8060	η Cap 5	Middle Cap*	Middle Cap*
	8260	ε Cap 4	Middle Cap*	Middle Cap*
	8288	κ Cap 4	Middle Cap*	Middle Cap*
	8709	δ Aqr 3	Feet Aqr*	Feet Aqr*
	8670	68 Aqr 5	Feet Aqr*	Feet Aqr*
	74	ι Cet <3	Tail Cet*	Tail Cet*
	188	β Cet 3	Tail Cet*	Tail Cet*
	818	τ^1 Eri 4		Bend Eri
	1865	α Lep 3	Lep*	Lep*
	1829	β Lep 3	Lep*	Lep*
	2294	β CMa 3	Feet CMa	Feet CMa
	2387	ξ^1 CMa 5	Feet CMa*	Feet CMa*
	2827	η CMa <3		Tail of CMa*

	3045	ξ Pup 4	Pup	Stern Pup*
	3034	o Pup 4	Pup	Stern Pup*
	3185	ρ Pup 3	Pup	Stern Pup*
	3468	α Pyx 3	Pup	Mast Pup*
	3438	β Pyx 3	Pup	Mast Pup*
	5231	ζ Cen >3	Back Cen	Back Cen
	4819	γ Cen 3	Back Cen	Back Cen
	4802	τ Cen 4	Back Cen	Back Cen
	5190	ν Cen >4		Breast Cen
	5248	φ Cen >4		Breast of Cen
	6527	λ Sco 3	Sting Sco*	Sting Sco*
	6508	υ Sco 4	Sting Sco*	Sting Sco*
	6859	δ Sgr 3	Bow of Sgr*	
	6879	ε Sgr 3	Bow of Sgr*	
	6913	λ Sgr 3	Bow of Sgr*	
	6812	μ Sgr 4	Bow of Sgr*	
	7194	ζ Sgr 3		Sgr
	7292	ψ Sgr 5		Sgr
	7234	τ Sgr >4		Sgr
	7597	ω Sgr 5		Sgr
	5708	ε Lup 4		Lup
	5626	λ Lup 5		Lup
	5605	π Lup 5		Lup

Table 1.
Stars defining the Tropics of Cancer and Capricorn and the Celestial Equator. The identification of stars marked with an asterisk is considered to be good.

[1] *Hoffleit 1982. We use the standard abbreviations for the constellations: Ari=Aries, And=Andromeda, Aql=Aquila, Aqr=Aquarius, Aur=Auriga, Cap=Capricornus, Cet=Cetus, Cma=Canis Major, Cnc=Cancer, Cen=Centaurus, Crt=Crater, Crv=Corvus, Cyg=Cygnus, Eri=Eridanus, Gem=Gemini, Her=Hercules, Hya=Hydra, Lep=Lepus, Lib=Libra, Lup=Lupus, Oph=Ophiuchus, Ori=Orion, Peg=Pegasus, Per=Perseus, Psc=Pisces, Pup=Puppis, Pyx=Pyxis, Sco=Scorpius, Ser=Serpens, Sgr=Sarittarius, Tau=Taurus.*

250 BCE but before the year zero. Although a few stars were within ± 2½° of their circles for many centuries (o Pup), others were there in the early years and then became more distant (η Cap). Still others are within this interval only later (α Lep). Some of the stars which first come within the interval at later dates are those which according to our hypothesis have been added by the Mycenaeans or the Greeks.

We see that there are more than twice as many stars within 2½° in the years around 2000 BCE, when the Minoan culture was reaching its height, than there are

Cancer	3250	3000	2750	2500	2250	2000	1750	1500	1250	1000	750	500	250	0
α Gem*	X	X	X											
β Gem*	X	X	X	X	X									
χ Aur								X	X	X	X			
θ Per*	X	X	X	X										
ξ Per*									X	X	X	X		
ι And*				X	X	X	X	X						
κ And*		X	X	X	X	X	X							
λ And*	X	X	X	X										
χ And					X	X	X	X						
ρ And*										X	X	X	X	X
π Peg*											X	X	X	X
κ Peg*														
φ Cyg*														
η Cyg*														
ε Cyg*	X	X	X	X	X	X	X	X	X	X				
β Oph*														
γ Oph*														
ι Oph*				X	X	X	X							
κ Oph*			X	X	X	X								
α Oph*				X	X	X	X							
ω Her									X	X	X	X		
β Ser*												X	X	X
δ Ser*								X	X	X	X			
λ Ser*						X	X	X						
α Ser*					X	X	X	X						
ε Ser*			X	X	X	X								
η Leo*													X	X
α Leo*	X	X	X	X	X	X	X	X	X	X	X	X		
31 Leo*	X	X	X	X	X	X	X	X	X					
ν Leo*	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ρ Leo*	X	X	X	X	X	X	X	X	X	X				
53 Leo*					X	X	X	X	X	X	X	X		
ι Leo*									X	X	X	X	X	
η Cnc*			X	X	X	X	X	X	X	X	X	X	X	X
θ Cnc*						X	X	X	X	X	X	X	X	X
γ Cnc*	X	X	X	X	X	X	X							
δ Cnc*			X	X	X	X	X	X	X	X	X	X	X	X
Equator	3250	3000	2750	2500	2250	2000	1750	1500	1250	1000	750	500	250	0
α Ari*			X	X	X	X								
β Ari*					X	X	X	X						
η Ari*					X	X	X							
θ Ari*						X	X	X						
ν Ari*				X	X	X								
ε Ari*				X	X	X	X							
μ Tau*													X	X

90 Tau*							X	X	X	X	X	X		
δ Ori*														
ε Ori*														
ζ Ori*														
ι Hya*														
β Crt*	X													
α Crt*	X	X	X	X	X	X	X							
γ Crt*				X	X	X	X	X	X					
δ Crt*							X	X	X	X	X	X		
α Crv*	X	X	X											
ε Crv*	X	X	X	X	X									
ζ Crv*		X	X	X	X	X								
β Crv*	X	X	X	X	X									
ι Lib*					X	X	X							
γ Lib*								X	X	X				
η Oph*			X	X	X	X								
ζ Oph*								X	X	X	X			
γ Aql														
ν Peg*														
θ Peg*														X
ζ Peg*										X	X	X	X	X
ξ Peg*								X	X	X	X	X	X	
γ Peg*									X	X	X	X		
τ Psc*														
ψ1 Psc*				X	X	X	X							
ψ2 Psc*					X	X	X	X						
χ Psc*					X	X	X	X						
υ Psc*	X	X	X											
φ Psc*	X	X	X	X	X									
ψ3 Psc*						X	X	X	X					
Capricorn	3250	3000	2750	2500	2250	2000	1750	1500	1250	1000	750	500	250	0
φ Cap*	X	X												
η Cap*	X	X	X	X	X	X								
ε Cap*														
κ Cap*														
δ Aqr*														X
68 Aqr*														
ι Cet*									X	X	X	X		
β Cet*														
τ1 Eri														
α Lep*								X	X	X	X	X	X	
β Lep*											X	X	X	X
β CMa			X	X	X	X	X	X						
ξ1 CMa*									X	X	X	X	X	X
η CMa*														
ρ Pup*	X													

ξ Pup*	X	X	X	X	X	X	X	X					X	X
o Pup*	X	X	X	X	X	X	X	X	X	X	X	X	X	X
α Pyx*	X	X	X	X	X	X	X	X	X	X	X			
β Pyx*														
ν Cen							X	X	X	X				
φ Cen							X	X	X	X				
ζ Cen			X	X	X	X								
γ Cen	X	X	X	X										
τ Cen	X	X	X	X	X									
λ Sco*				X	X	X	X							
υ Sco*				X	X	X	X							
δ Sgr*							X	X	X	X	X			
ε Sgr*			X	X	X	X								
λ Sgr*													X	X
μ Sgr*														
ψ Sgr							X	X	X	X	X	X	X	X
τ Sgr					X	X	X	X	X	X				
ζ Sgr					X	X	X	X						
ω Sgr		X	X	X	X	X								
ε Lup				X	X	X	X							
λ Lup				X	X	X	X							
π Lup			X	X	X									
	3250	3000	2750	2500	2250	2000	1750	1500	1250	1000	750	500	250	0
TOTAL	25	26	35	43	50	48	44	37	32	31	27	23	19	18

Table 2.
Stars within ± 2½° of the Tropic of Cancer, Capricorn or the Celestial Equator at 250-year intervals from 3250 BCE to 0.

in the period between 500 and 250 BCE, the time closest to when Eudoxos and Aratos were writing their *Phainomena*. This seems unlikely to be a random result. Still we decided to compare it with how the 1028 stars in Ptolemy's catalogue relate to the same circles for the same years (Table 3).[20] We found that the percentage of stars in the catalogue which lie within ± 2½° of the Tropics and the Celestial Equator is lower around both years and considerably lower around the year 2000 BCE. We interpret this to mean that the stars given by Aratos were deliberately chosen because of their

Source	2000 BCE	500 BCE
Ptolemy	16.5%	15.8%
Aratos and Eudoxos	42.0%	20.5%

Table 3.
Percentage of stars within ± 2½° of the Tropics of Cancer and Capricorn and the Celestial Equator, from Ptolemy's catalogue (n=1028) and from Aratos and Eudoxos (n=111) calculated for the years 2000 and 500 BCE.

proximity to the respective circles and that the initial choice was more likely to have been finalized by ca 2000 than 500 BCE.

As to the second part of our hypothesis, that the system was modified as stars became more distant to their horizon points, we should keep in mind that such a system, based as it was on knowledge of the motions of the heavenly bodies, would almost certainly have had a religious dimension. There are likely to have been strong religious attitudes counteracting modification. If the choice of stars was made with the rising and setting of the sun at the solstices and equinoxes as the guiding principle, then this suggests an original conception of a procession of divine figures, the constellations, as a train following the sun as it rose and set at the major points in the calendar.

When the feasibility was recognized of using the 'train' to teach and use the positions of the stars for navigation, the parts of constellations which served this purpose best would have been singled out. Although individual stars were used in practice, reference, for religious reasons, would have been to the figures in the train, the constellations, or to their parts. Also for religious reasons the choice would not have been limited to the most practical constellations, but those of important nearby figures would have been included. Rules of thumb would have been devised so that such figures would have functioned in the system. This would explain the inclusion of Orion, for example, which may have represented the double axe for the Minoans (as described by α, γ, δ, ϵ, ζ, κ and β Ori).

There are other factors which would have worked against any modification of the system. The stars or constellations were almost certainly regarded as divine and this in good measure because they were believed to be perfectly regular in their motions. Aratos says of the constellations, "These you can see as the years pass returning in succession; for these figures of the passing night are all well fixed in the sky just as they are."[21] Moreover, since precession is so slow, changes in stellar positions would have been appreciable only after several generations had passed. When the discrepancies became apparent, the most likely explanation would have been that the observers of earlier times had been mistaken. For reasons such as these we consider it unlikely that the Minoans would have altered the system at all, but would have developed techniques for dealing with the changes.

However, members of another culture with a different religion taking up the system would have been much freer to go in and make changes. If the take-over entailed translation to a different language, revision would have been more opportune. This calls to mind, of course, the Mycenaeans who most likely adapted the system for their uses just as they adapted Linear A for writing their language. Yet even in such a case, the choice of deletions and inclusions would probably not have been solely practical. A star would not have been removed from the list only because it had moved to a distance greater than ± 2½° from its earlier position. There are likely to have been several factors influencing such a decision. And we must not forget that an exact figure such as 2½ would certainly not have been used by the Minoans, the Mycenaeans or the Greeks. This is a requirement imposed by the modern computer.

Statistical tests

Two statistical tests were applied to our data. One was the sign test,[22] made with the following assumptions: 1) the stars were selected at a single point in time; 2) the selection can be approximated as an independent selection with replacement and 3) the time a star rose or set closest to the respective rising and setting points could lie with equal probability in the future as in the past. The following stars were excluded as not helpful in determining when the initial selection had been made: those never within 2½° (κ Peg) and those whose change in position at approximately the year 500 was less than 2½° in 1000 years (ρ And). The 18 less certainly identified stars (those without asterisks in Table 1) were weighed as half and the stars which could be assumed to belong to the same selection were placed in the same group (the hand of Andromeda or ι, κ, λ And). The number of such groups is 33. To weigh the result negatively, the calculations were made using only the star in each group which appears latest (for example ι And). The year 600 was chosen for the null hypothesis, where the assumption that the initial selection was made after 600 could be rejected at the significance level of 0.05. The result showed a systematic shift backwards in time from the year 350, and with 95% certainty either the initial selection of stars occurred before the year 600 or there must be another explanation for the shift. As the test was weighed negatively, we can assume an even earlier date.

The second statistical test is the calculation of the mean deviation, regardless of size, of each of the 111 stars from their rising and setting points at 250-year intervals from 3250 to the year 0. The result shows that the deviation was lowest at about 2000 BCE (Fig. 1). The error can be estimated at about 100 years. In this test all data weigh the same.

Conclusions and summary

Three independent evaluations—the two statistical tests and the comparison with the distribution of stars in Ptolemy's catalogue (Table 3)—point to the deliberate

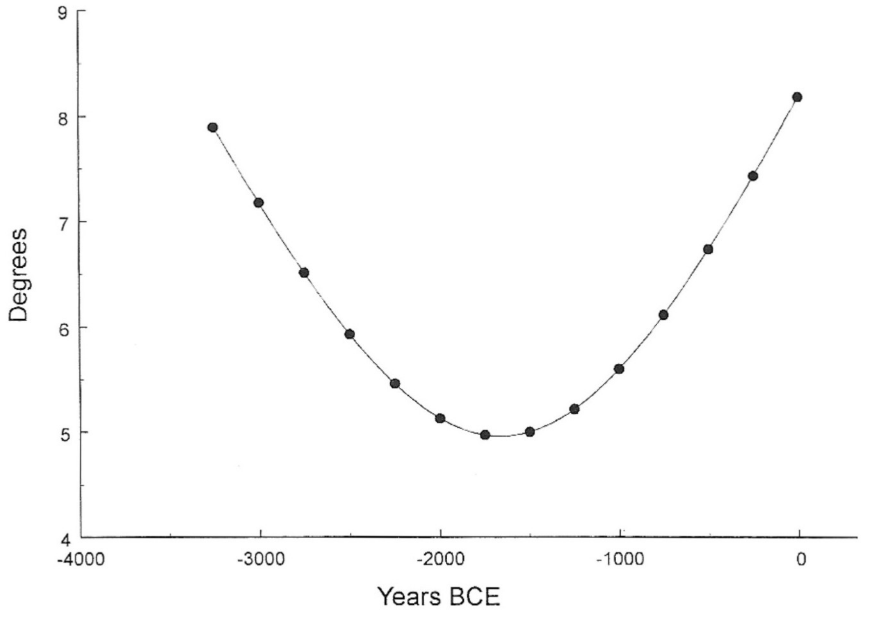

Fig. 1.
Mean deviation of the 111 stars from their respective circles, calculated at 250-year intervals.

selection of the stars which Aratos and Eudoxos used to define the great circles at a date long before their own time.

In view of all the evidence, we consider it a reasonable conclusion that the astronomical information contained in Aratos and Eudoxos is part of an oral tradition of didactic poetry going back to the Minoans in which knowledge was preserved in easy-to-remember verse and then learnt by rote. Such rote learning of lengthy works is typical of cultures with limited reliance on writing and was still customary in Greece in the Classical Period.[23] Oral transmission of the astronomical knowledge required for stellar navigation was the method relied upon in the South Pacific until recently.[24] If the astronomical knowledge of the Minoans was preserved in this way, it was most likely translated at some point into Mycenaean Greek, as the Mycenaeans became the inheritors both of Minoan culture and the Aegean hegemony in the Late Bronze Age. They would surely have taken up the astronomical knowledge and navigational skills of the Minoans. Much of the information about the positions of the stars, however, would have been at odds with the appearances by the time

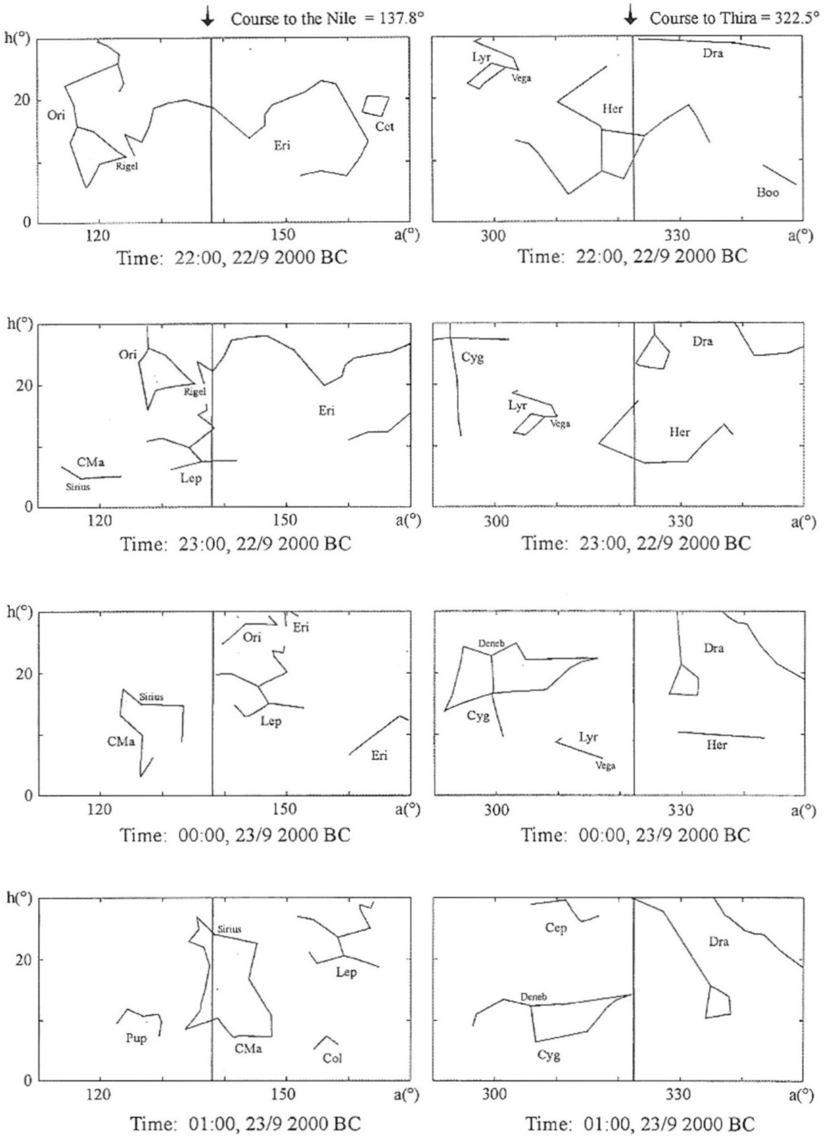

Fig. 2.
Constellations in the direction to the Nile Delta from the Minoan harbor town below Petsophas (left) and to Thera from Cape Sideros, just north of the same town (right).

the Mycenaeans took it up and this could have led to revision in connection with translation.

Of course, it is not the *possibility* of stellar navigation that is at issue. This is amply demonstrated in the ancient and still living tradition in the South Pacific.[25] The native pilots in that region can accurately navigate over hundreds of miles of empty, open water relying solely upon their knowledge of the motions of the heavenly bodies, the winds and the currents. They use no instruments at all while at sea. What we wish to present here is the evidence that the Minoans had the astronomical knowledge adequate for stellar navigation and also boats capable of sailing in the Mediterranean.

In Fig. 2 we see how the sky would have appeared through the night of September 22-23, 2000 BCE, to a Minoan pilot on course to the Nile Delta or to the island of Thera from the Minoan harbor town which lay near modern Palaikastro, on the northeastern coast of Crete. The course to Thera is the same as the one to Siphnos and Attika from where the Minoans could have been getting metals in the Early Bronze Age.[26]

The pilot would have maintained a predetermined relationship between the parts of the boat and the rigging to relevant stars—both in front of and behind the boat—when these had reached an altitude of between about 10° and 20°, which is the most convenient for use in navigation (Fig. 3). The knowledge which the pilot relied upon to plan and keep his course would have been acquired partly from theoretical study of the stars, partly from experience at sea. The view of the night sky in Fig. 3 reminds us of the following lines in Aratos:

> Now too a sailor on a clear night at sea can observe the first bend of the River (Eridanus) emerging from the sea, as he waits for Orion himself, to see if a sign will at some point predict for him the length of either the night or the voyage; for everywhere the gods give these many predictions to men (lines 728-732).[27]

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1 Stos-Gale and Macdonald 1991, 268-269; Williams-Thorpe 1995, 231-2.

2 Basch 1987, 99-101; Betts 1973; we follow the chronology argued for by Manning 1995.

3 Wachsmann 1998, 12-18; Landström 1970, 63-69.

4 Morgan 1988, 121-142 and pls. 9-11; Georgiou 1991.

5 Georgiou 1993, 361.

6 Blomqvist 1979, 8-11.

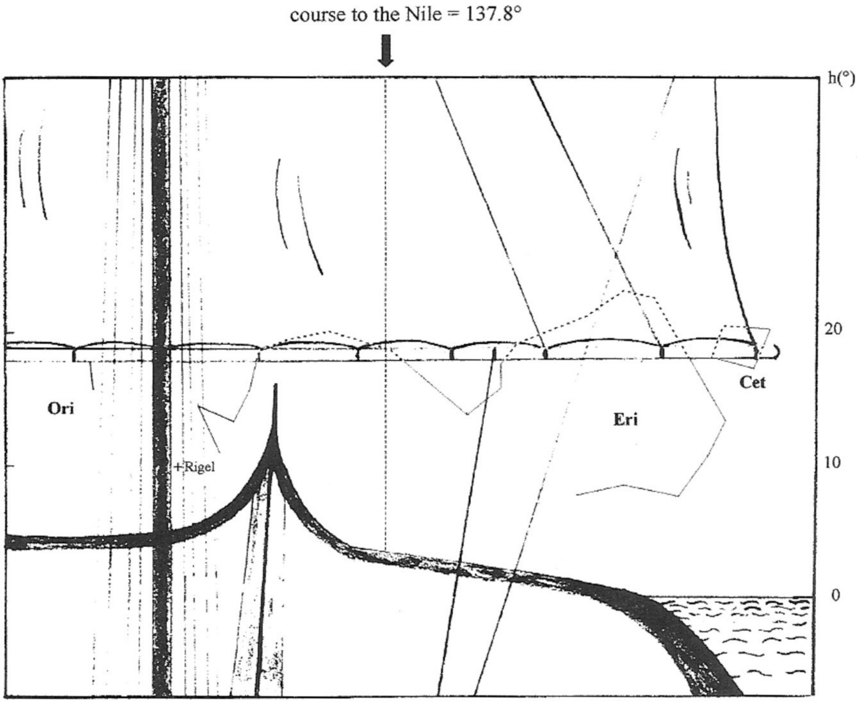

Fig. 3.
Illustration of the relationship between a Minoan boat of the Late Minoan Period and the constellations relevant for sailing to the Nile Delta from the northeastern coast of Crete at 10 pm on the 22nd of September 2000 BCE. Drawing by Anna Wærn-Sperber.

7 The peak sanctuaries on Petsophas, Traostalos, Juktas, Pyrgos, Gonies, Vrysinas; the palaces at Knossos, Gournia, Mallia, Phaistos, Zakros; the villas at Agia Triada, Tylissos, Vathypetro.

8 Blomberg and Henriksson 1996; Henriksson and Blomberg 1996; 1997-1998; 2005.

9 Catling 1973-74, 34; Shaw 1977, 48. We are very grateful to Mr. Sinclair Hood for pointing out to us the course of the earlier building.

10 Blomberg and Henriksson 1996, 37-39.

11 Hom. *Od.* 5.270-277.

12 Hom, *Il.* 10.261-265. Other examples may be found in Nilsson 1972, 137-150.

13 *Aratus: Phaenomena* 1997. We use the original spelling for Greek authors and titles except when citing works by modern authors.

14 *Hipparchi in Arati et Eudoxi Phaenomena* 1894; *Die Fragmente des Eudoxus* 1966.

[15] Ovenden 1961, 94; Ovenden 1966, 15.
[16] *Aratus: Phaenomena* 1997, lines 26-35, 71-73.
[17] Dicks 1970, 161.
[18] Henriksson and Blomberg 1996; 1997-1998.
[19] *Aratus: Phaenomena* 1997, lines 480-524; *Hipparchi in Arati et Eudoxi Phaenomena* 1894, 1.2; *Ptolemy's Almagest* 1984, 341-399; Sanford 1989.
[20] *Ptolemy's Almagest* 1984, 341-399.
[21] *Aratus: Phaenomena* 1997, lines 451-453.
[22] Larsen and Marx 1986, 552. We are grateful to Stefan Israelsson for his help with the statistical evaluation.
[23] Thomas 1992, 113-117.
[24] Lewis 1972.
[25] Lewis 1972.
[26] Stos-Gale and Macdonald 1991, 268-269.
[27] *Aratus: Phaenomena* 1997, lines 728-732.

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