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Abstract: Archaeo astronomy normally consists of interpreting available data and archaeological evidence about the astronomical knowledge of a civilisation. In the present study, we attempt to 'reverse engineer' and attempt to define the nature of astronomy of a civilisation based on other evidence of its cultural complexity. We then compare it with somewhat sketchy data available so far and suggest the possible manner in which their observatories can be identified.

1 INTRODUCTION

The Harappan civilisation lasted from about 7,000 BC to 2,000 BC. At its peak it spread over an area of more than a million square kilometres, and boasted more than 5,000 rural centres, over a dozen which had population densities >3 per m^2 (Kenoyer, 1998, Possehl, 2002, Agarwal, 2007, Wright 2010). Harappan culture evolved and merged and transformed over this period (Gangal et al., 2011), and it also went through a complex evolutionary pattern (Vahia and Yadav, 2011a). It was the most advanced pre-iron civilisation in the world.

It is no surprise, therefore, that the Harappans had a vibrant intellectual tradition. This can be seen in their art work (Vahia and Yadav, 2011b) and writing (see e.g. Yadav et al., 2010). They must also have had an active astronomical tradition since astronomy and myths arise very early in civilisations and evolve with increasing complexity (Vahia and Yadav, 2011c). In the present study we examine the foundations of Harappan observational astronomy, note what would have been of particular interest to the Harappan astronomers, and query whether any evidence of their activities is likely to be found in the archaeological record.

2 Discussion of Harappan Astronomy

Parpola (1994; 198:210) has extensively speculated on the possible astronomical and astrological background of Harappan Civilisation. Basing these ideas on his conviction of the connection between Harappan Civilisation Parpola points out that the Nakshtatras (Lunar mansions) appear fully formulated in the 10th book of Rig Veda without detailed evolutionary discussions suggesting that they were directly included from an external source that he attributes to the Harappans. Similarly, he suggests that the luni-solar calendar (and its synchronisation) that is in vogue in the Vedic literature is of no use to the nomadic people but are crucial for administration in cities and hence must be a Harappan patch. Using these and other arguments, Parpola 1994 concluded that Harappan astronomy must have been strong and left behind a significant impact on later civilisations.

3 THE RISING AND SETTING DATES OF IMPORTANT STARS

From rock art records dating back for several millennia we know that humans noticed the movement of the Sun, the Moon, the planets and certain stars long before the emergence of advanced civilisations. It is therefore a simple assumption that the Harappan astronomers must have been ardent observers of the sky. They would have needed celestial knowledge for

(1) calendrical purposes, including prediction of seasons;
(2) directional and navigational purposes; and
(3) astrological purposes, since the heavens were the abode of the gods.

Meanwhile, astronomy would have been a fascinating object of study in its own right, pandering to their innate curiosity, as was the case in many cultures around the world.

The Harappan astronomers would therefore have had star names, constellation names and possibly names for the zodiac as well as different lunar mansions. However, we have no idea whether their astronomy was based on the Sun, the Moon or the stars. There is extensive archaeological evidence that the Harappans traded with cultures in West Asia ((Kenoyer, 1998), Possehl, 2002)). The constellations as we know them today were formalised in Mesopotamia around 3000 BC ((see for example Wikipedia entry on "History of Constellations"), a few centuries before Harappan civilisation, and hence it can be assumed that the Harappan astronomers also identified and used many of the same constellation patterns. However, lunar mansions are another story, as the concept did not arise in West Asia, but was borrowed from the Indian Subcontinent and incorporated much later, which suggests an Harappan influence or origin(see e.g. Vahia, 2008).

Table 1: Data on the rising and setting of the twenty-five brightest stars.*

Sl. No.	Name	Scie. name	Mag	Rise date				Set Date				Rise locn	Set locn
				At sunrise 6.30 am		At sunset 7.30 pm		At Sunrise 6.30 am		At sunset 7.30 pm		Degrees from North	
				Date	DOY	Date	DOY	Date	DOY	Date	DOY		
1	Sirius	α CMa	–1.09	June 15	166	Nov 29	333	Nov 19	323	May 4	124	112	247
2	Canopus	α Car	–0.62	Aug 15	227	Jan 29	29	Oct 31	304	April 13	103	165	200
3	Rigel Kentaurus	α Cen	–0.01	Oct 20	293	April 5	95	Feb 27	58	Aug 12	224	135	225
4	Vega	α Lyre	–0.05	Nov 14	318	April 28	118	Jul 12	193	Dec 27	361	42	320
5	Arcturus	α Boo	–0.05	Aug 18	230	Feb 3	34	Apr 23	113	Oct 6	279	36	322
6	Betelgeuse	α Ori	0.00	May 15	135	Oct 29	302	Nov 7	311	April 23	113	100	263
7	Capella	α Aur	0.08	April 2	92	Sept 17	260	Nov 4	308	April 20	110	58	305
8	Rigel	β Ori	0.17	May 23	143	Nov 5	309	Oct 23	296	April 7	97	115	245
9	Procyon	α CMi	0.4	June 5	156	Nov 17	321	Dec 7	341	May 23	143	82	278
10	Achernar	α Eri	0.46	Circumpolar to South Pole not visible at Harappa									
11	Hadar	β Cen	0.61	Oct 8	281	March 23	82	Feb 17	48	Aug 2	214	135	225
12	Aldebaran	α Tau	0.75	April 22	112	Oct 5	278	Oct 18	291	March 31	90	93	268
13	Altair	α Aql	0.76	Dec 8	342	May 24	144	June 18	169	Dec 2	336	78	282
14	Acrux	α Cru	0.76	Sept 26	269	March 12	71	30 Jan	30	Jul 17	198	137	225
15	Spica	α Vir	0.95	Aug 27	239	Feb 11	42	March 11	70	Aug 24	236	75	285
16	Antares	α Sco	0.96	Oct 20	293	April 4	94	April 12	102	Sept 25	268	97	262
17	Pollux	β Gem	1.16	May 14	134	Oct 28	301	Dec 11	345	May 26	146	62	295
18	Fomalhaut	α PsA	1.16	Feb 13	44	Aug 1	213	Jun 7	158	Nov 22	326	145	218
19	Deneb	α Cyg	1.25	Dec 20	354	June 6	157	Aug 5	217	Jan 18	18	45	312
20	Becrux	β Cru	1.25	Sept 24	267	March 10	69	Feb 6	37	July 22	203	132	230
21	Regulus	α Leo	1.36	June 25	176	Dec 9	343	Jan 20	20	Jul 6	187	62	295
22	Adhara	ε CMa	1.5	July 3	184	Dec 16	350	Nov 20	324	May 6	126	130	230
23	Castor	α Gem	1.57	May 7	127	Oct 21	294	Dec 8	342	May 24	144	59	302
24	Gacruz	γ Cru	1.63	Sept 20	263	March 4	63	Feb 5	36	Jul 21	202	135	230
25	Shaula	λ Sco	1.63	Nov 7	311	April 23	113	April 13	103	Sept 27	270	115	248

*Note that the list excludes stars from some very conspicuous constellations such as Ursa Major (*Saptarshi*) since none of the stars in these constellations are very bright.

Harappans would also have marked the rising and setting locations of various stars and their relations to the seasons and to the calendar. In Table 1 we give the rising location of 25 of the brightest stars in the night sky as seen from the longitude of New Delhi in 2500 BC (taken from Skymap Pro 11). It is important to note that at this time the present Pole Star was very far from the North Celestial Pole due to precession (for a detailed discussion on this, see below). The 3.7 magnitude star Thuban, in the constellation of Draco, was probably the closest, having been exactly at the Pole in 2787 BC. Therefore, it would have been relatively easy for the Harappan astronomers to align their observatories to the north and they could have built their cities aligned to Thuban assuming it to be the Pole Star. This may explain why Harappan cities are aligned at a small angle from the north. In Table 2, we give the angle of Thuban from the north as a function of time.

Table 2: The angular distance of Thuban from the north as a function of date.

Year (BC)	Thuban's angle from exact north (note that actual movement is much higher)
3000	1.7 deg West of North
2750	0.2 deg East of North
2500	1.8 deg East of North
2250	3.4 deg East of North
2000	4.8 deg East of North

4 CHANGES IN THE EARTH'S ORBIT

The seasons arise because the tilt of the Earth's axis of rotation relative to the plane of revolution around the Sun. This tilt is 23.44°. In addition to this, the land mass distribution in the northern and southern hemispheres is different, with about 79% (above sea level) being in the Northern Hemisphere and only 21% is in the Southern Hemisphere. Land has a much lower specific heat compared to water and hence it heats up much faster for the same amount of heat received from the Sun. Hence the temperature of the Earth crucially depends on how much solar radiation is received by land compared to water.

The Earth's orbit around the Sun is not constant and keeps changing with time. Hence the heating of the Earth as a whole also changes with time. There are three specific changes that happen during the orbiting of the Earth around the Sun. These are: changes in the eccentricity of the Earth's orbit, variation in the inclination of the Earth's axis of rotation and precession of perihelion. These are illustrated below in Figure 1.

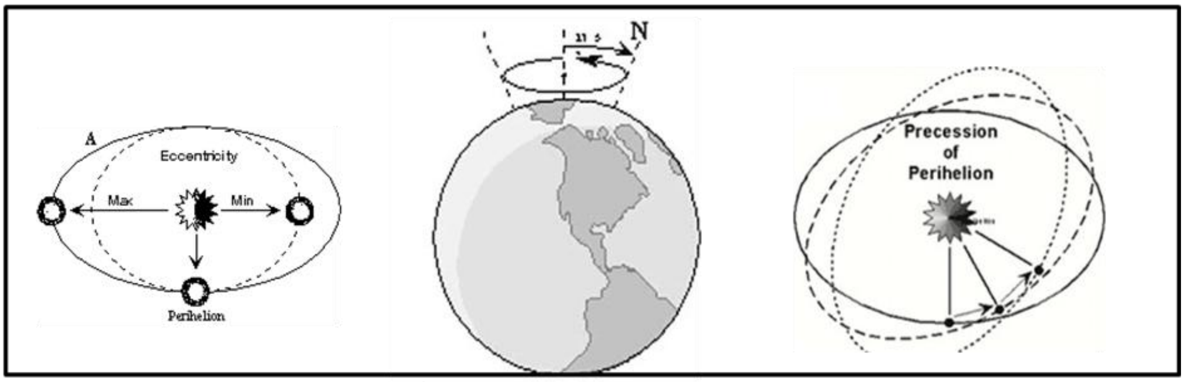

Figure 1a: Change in ellipticity of Earth's orbit

Figure 1b: Wobble of the Earth's orbit

Figure 1c: Precession of the Earth's orbit

Figure 1: Changes of the Earth in its orbit round the Sun, with the passage of time. Left: eccentricity; centre: the axis of rotation; and right: precession (after http://geology.uprm.edu/Morelock/eustatic.htm).

4.1 Long-term Variations in these Parameters

In Table 3 we give the time scale of variability of these parameters.

Table 3: Variations in the various parameters.

Parameter	Time scale (years)	Level of variation	Present value
Ellipticity	95,000; 131,000; and 404,000	0.00 to 0.06	0.017
Obliquity	41,000	22.0 to 24.6	23.44
Precession	26,000	At present the northern hemisphere faces away from the Sun at the point of closest approach	

In Figure 2, the changes in these parameters are graphically represented. As can be seen from this figure, variation in the obliquity of the orbit has not been significant in the last 10,000 years (that concern us here). Similarly, the eccentricity of the Earth's orbit has also not changed significantly over this period. Therefore, the only effect of consequence for us is the precession of the Earth's orbit, and we will ignore all other effects in the subsequent discussion.

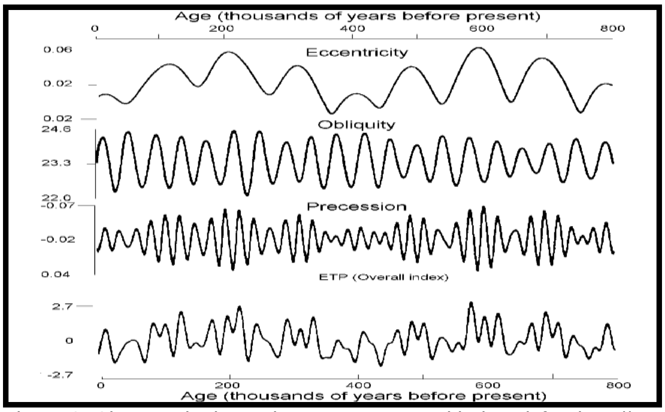

Figure 2: Changes in the various parameters with time (after http://geoinfo.amu.edu.pl/wpk/pe/a/harbbook/c_viii/chap08.html).

5 PRECESSION OF THE EARTH'S ORBIT, AND THE SEASONS

The precession of the Earth's orbit and its affects are shown graphically in Figure 3. As can be seen from the figure, the difference between perihelion, the point of closest approach (146 million km), and aphelion, the farthest distance (151 million km), is about 3%. However, the seasons on Earth are a complex combination of the distance from the Sun and the tilt of the Earth's rotational axis. This primarily changes the amount of radiation received on any part of the Earth as a function of time. In Table 4 we tabulate the quantities discussed in Figure 3.

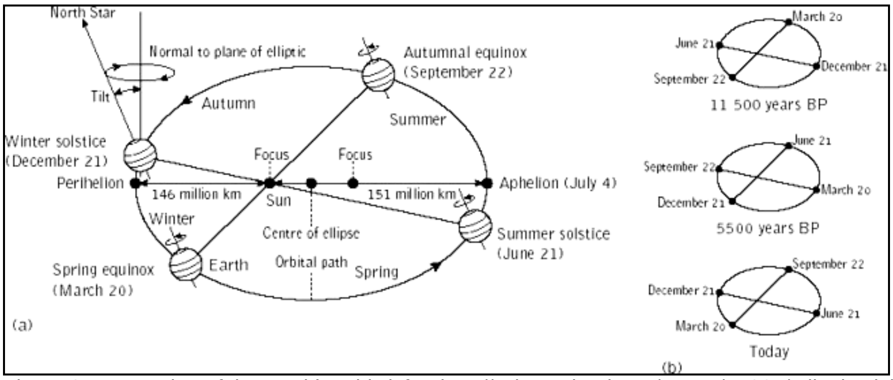

Figure 3: Precession of the Earth's orbit (after http://science.jrank.org/pages/47865/Milankovich-cycles-climate-change.html).

Table 4: Drift in solstice and equinox times over the last 12,000 years.

Date	SE*	SS	AE	WS	P	A	Comments
Present	March 20	June 21	September 22	December 21	January 3	July 4	Cool and long summers, warm winters in the north
5,000 BP	December 21	March 20	June 21	September 22	October 6	March 3	Intermediate
11,500 BP	September 22	December 21	March 20	June 21	July 4	January 3	Cold and long winters, hot and short summers in the north

* Key: SE: spring equinox; SS: summer solstice, AE: autumn equinox, P: perihelion, A: aphelion.

Based on the data in this Table, we define the four seasons (Figure 4) as:

(1) Summer: From summer solstice (maximum declination) until autumn equinox (declination = 0)
(2) Autumn: From autumn equinox (declination = 0) until winter solstice (minimum declination)
(3) Winter: From winter solstice (minimum declination) until spring equinox (declination = 0)
(4) Spring: From spring equinox (declination = 0) until summer solstice (maximum declination)

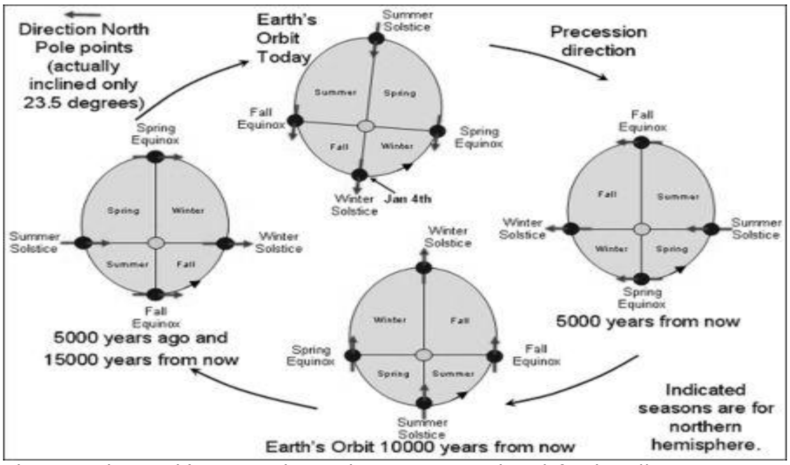

Figure 4: The Earth's precession and seasons over time (after http://www.answers.com/topic/milankovitch-cycles)

Based on this, we can define the period of the various seasons over the millennia. As can be seen from Figure 4, at the time of the Harappan civilisation, the spring was 94 days long, summer was 90 days long, autumn was 89 days long and winter was 92 days long.

However, the seasons in the Indian Subcontinent are driven by a different set of parameters compared to what happens at higher latitudes (from which we had taken the earlier definition since the Sun never comes overhead in higher latitudes). For the Subcontinent we can define the seasons as follows:

(1) Summer: spring equinox to summer solstice
(2) Monsoon: summer solstice to a month after autumnal equinox, making this the longest season
(3) Winter: A month after autumnal equinox to a month after winter solstice
(4) Spring: A month after winter solstice to spring equinox, making this a short season.

The affect of these on the seasons is complex since the weather pattern in the Subcontinent is driven by the following parameters:

(1) The evaporation in the southern hemisphere while it is winter in the north (around January in the present Epoch)
(2) The movement of the moisture to the equatorial latitudes at Summer solstice (around March in the present epoch)
(3) The amount of heating of the Indian subcontinental plate in early summer (around May – June in the present epoch)
(4) The wind patterns in late summer (July to October in the present epoch).

Hence, while the intensity of the monsoons is difficult to predict, the months in which they will appear can be estimated and is given in Table 5, along with the duration of the seasons in Table 6. Table 6 clearly shows that the period in which the various seasons occurs varied significantly with time.

Table 5: The period of the various seasons in Harappan civilisation.

Date	Summer	Monsoon	Winter	Spring
	SE to SS	SS to after AE	After AE to after WS	After WS to SE
Present	April - June	July – October	November - February	March – April
5,500 BP	December – February	March – July	August - October	November – December
11,500 BP	October - December	January - April	April - July	August – September

Table 6: Duration (in days) of the various seasons in the Harappan region.

Date	Summer	Monsoon	Winter	Spring
Present	92	124	90	59
5,500 BP	89	122	94	60
11,500 BP	90	119	92	64

However, no archaeological data is sensitive to the variations of the kind discussed above. On the other hand the astronomical records of the period will certainly be sensitive to the seasons. In Table 7 we list all the stars that the Harappan astronomers would have seen near the horizon at the beginning and end of each season. Somewhere in the Harappan civilisations, there must have been markers for the rising and setting points of some of these stars (see Table 2 for their rising and setting locations). In Table 8, we list all the conspicuous constellations in the sky during the different seasons.

Table 7: Principal stars and constellations in 3000 BC, at the time of the equinoxes and solstices.

Period	Date in 3000 BC	Constellation			
		At Sunset (7.30 pm)		At Sunrise (6.30 am)	
		East	West	East	West
Winter Solstice	December 21	Leo (Regulus), Orion	Cygnus (Deneb)	Cygnus (Deneb), Lyra (Vega)	Leo (Regulus)
Spring Equinox	March 20	Virgo (Spica) (Scorpio would rise soon)	Taurus (Aldebaran)	Piscis Austrini (Fomalhaut)	Virgo (Spica)
Summer Solstice	June 21	Cygnus (Deneb)	Leo (Regulus), Orion	Leo (Regulus), Orion	Cygnus (Deneb), Lyra (Vega)
Autumnal Equinox	September 22	Auriga (Capella)	Leo (Regulus), Orion	Virgo (Spica) (Scorpio would rise soon)	Leo (Regulus), Orion

Table 8: Important Constellations at Sunset in different seasons.

Season	Month	Constellations in the sky at sunset
Summer	December	Canis Minor, Gemini, Orion, Taurus, Lipus, Canis Major, Lyra
Monsoon	March	Bootis, Ursa Major, Auriga, Leo, Virgo, Cancer, Gemini, Taurus, Orion, Canis Major Lepus
Winter	August	Scorpio, Virgo, Bootis, Ursa Major Sagittarius, Aquila, Centaurus
Spring	November	Gemini, Taurus, Auriga, Aquila, Cygus, Orion, Ursa Major

6 SOLAR ECLIPSE OBSERVATIONS

The last important aspect of the Harappan civilisation is solar eclipses[1]. In Table 9 we list all prehistoric solar eclipses that would have been visible in the Harappan region between 1800 and 2000 BC, along with the maximum phase of the eclipse. The data in this table were taken from Espenak and Meeus (2009). The Time of Greatest Eclipse in Column 5 is in TT and the solar altitude and the path width in Columns 7 and 8 are for the location where the greatest eclipse is seen, so they are not related to the eclipse seen in Harappa. The percentage in the last column is based on the nature of maximum at the site.

Table 9: Prehistoric solar eclipses (after 2000 BC).

Sl. No.	Calendar date			Time of Greatest Eclipse	Type*	Solar altitude	Path width	% at Harappa
	Yr	Month	Day			Degrees	Km	
2	–1997	10	04	23:23:37	T	59	101	100
3	–1989	05	11	23:28:58	A	84	126	100
6	–1949	09	14	00:12:27	A	87	231	15

* T = total; A = annular

7 POSSIBLE STRUCTURES OF ASTRONOMICAL IMPORTANCE IN HARAPPAN CIVILISATION

Maula (1984) has suggested that the so-called 'calendar stones' found in Mohenjodaro (see Figure 5a) could have been used for astronomy, as shown in Figures 5b and 5c. However, this remains speculation since no clearly-mounted calendar stones have been found.

[1] Lunar eclipses, naked eye comets, meteor storms (like the Leonids, every 33 years), major planetary conjunctions, and supernovae would also have been conspicuous and drawn the attention of Harappan astronomers. However, at this early stage of studies, we do not consider them.

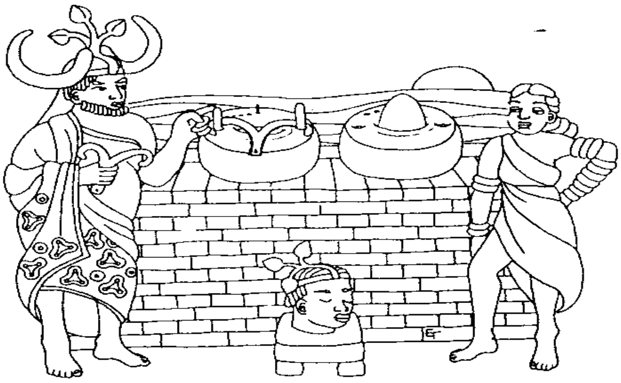

Fig. 5a: Calendar stone from Mohenjodaro Fig. 5b: Possible usage of calendar stone Maula (1984)

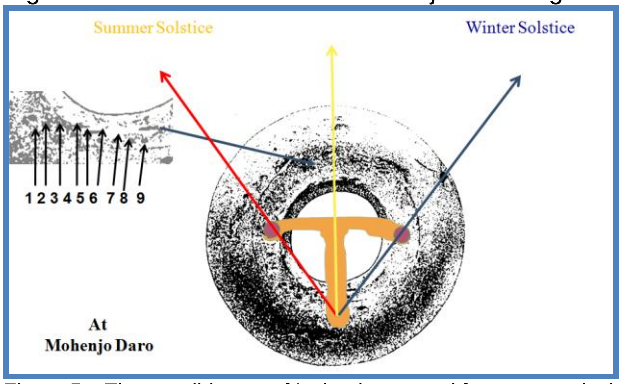

Figure 5c: The possible use of 'calendar stones' for astronomical observations (after Danino, 1984).

Another interesting piece of possible astronomical evidence is the circular stone structures at Dholavira (see Figure 6). These are clearly deliberately made, and they appear to point directly to the north. Stone circles that appear to have served as astronomical observatories were common in prehistoric India, where the rising and setting directions of important stars in specific cardinal directions were indicated by marker stones or by stones with cupmarks (e.g. see Figure 7). However, more work needs to be done to establish if the Harappan stone structures have astronomical significance.

Figure 6: A stone circle at Dholavira with a possible astronomical association.

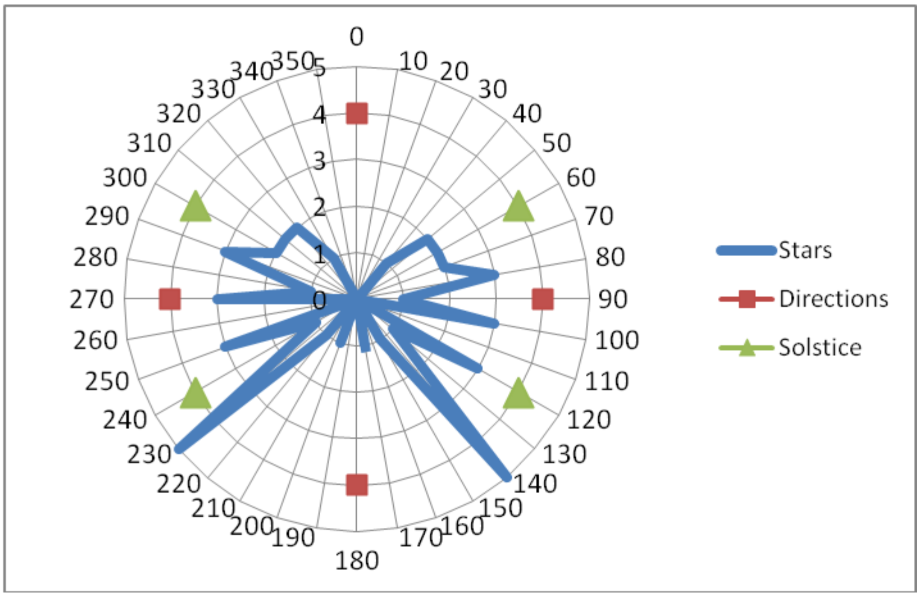

Figure 7: Important directions that were marked out in Indian stone circles.

8 STARS OF IMPORTANCE TO HARAPPAN CIVILISATION

In trying to identify the stars that most likely would have been considered important by the Harappans we can assume that by having a predominantly agricultural economy, the monsoons would have played a crucial role and stars indicating the arrival of monsoon would have been particularly important. Since the monsoon arrived in March, we list in Table 10 all those bright stars that rose in Harappa during the period February to April.

Table 10: The rising and setting times of selected stars that rose close to sunset during the monsoon season.

Sl. No.	No in Table 1	Name	Scientific name	Magnitude	Rise date		Set Date		Rise locn	Set locn	No of days in	
					At sunrise	At sunset	At Sunrise	At sunset	Degrees from North		Night sky	Not visible
					6.30 am	7.30 pm	6.30 am	7.30 pm				
1	3	Rigel Kentaur-us	Alpha Cen	–0.01	Oct 20	April 5	Feb 27	Aug 12	135	225	130	235
2	4	Vega	Alpha Lyr	–0.05	Nov 14	April 28	Jul 12	Dec 27	42	320	240	125
3	5	Arcturus	Alpha Boo	–0.05	Aug 18	Feb 3	Apr 23	Oct 6	36	322	245	120
4	11	Hadar	Beta Cen	0.61	Oct 8	March 23	Feb 17	Aug 2	135	225	132	233
5	14	Acrux	Alpha Cru	0.76	Sept 26	March 12	30 Jan	Jul 17	137	225	127	238
6	15	Spica	Alpha Vir	0.95	Aug 27	Feb 11	March 11	Aug 24	75	285	194	171
7	16	Antares	Alpha Sco	0.96	Oct 20	April 4	April 12	Sept 25	97	262	174	191
8	20	Becrux	Beta Cru	1.25	Sept 24	March 10	Feb 6	July 22	132	230	135	230
9	24	Gacruz	Gamma Cru	1.63	Sept 20	March 4	Feb 5	Jul 21	135	230	138	227
10	25	Shaula	Lambda Sco	1.63	Nov 7	April 23	April 13	Sept 27	115	248	157	208

As can be seen, only two of the stars in this table are northern stars (rising angle less than 90 degrees) while Spica and Anatares are in the east.Eight stars rose in the southern sky. Nevertheless, we can tentatively assume that the Harappan astronomers preferred the northern sky, on the basis that:

(1) Harappans traded predominantly with societies that were located to the north;
(2) They were ignorant of, and probably apprehensive about, what lay to the south; and
(3) The northern sky, with only three bright stars, was less cluttered than the southern sky where Orion and other prominent constellations were present, along with the brightest part of the Milky Way.

We therefore suggest that the Harappans worshipped Arcturus (α Bootis, or *Swati*), and a little later in the year Vega (*Abhijit*) Both showed similar celestial motion but Vega lagged behind by a couple of months, which would have created confusion for people reading the literature a few centuries later on. We choose Arcturus initially over Vega since Vega probably rose slightly *after* the monsoon started (in 2500 BC) and *Swati* was also a mansion through which the Moon passed.

Hence, at the time of the arrival of the monsoon or a little before that, Arcturus would have risen over the eastern horizon at sunset after being absent from the sky for approximately 117 days. Then when it disappeared over the western horizon (rising with the sunrise) in August, the winter would be coming to an end, indicating that the entire creative season was over and that hot summer days lay ahead. We give two additional pieces of evidence in possible justification of this suggestion. In Figures 8 and 9 we show the northern and the southern sky at the beginning of monsoon in 2500 BC. As can be seen, the northern sky is relatively uncluttered and has an excellent collection of identifiable stars which would make the identification and tracking of Arcturus and Vega easier. The southern sky, on the other hand, is far more cluttered, even though it has some important star clusters. Note that at this time the Saptarshi would have been parallel to the horizon.

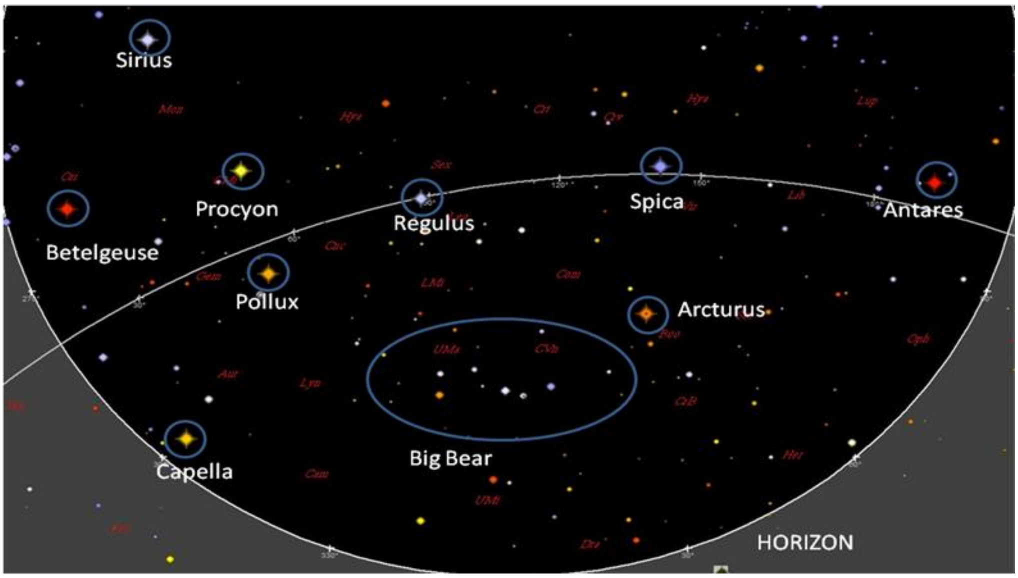

Figure 8: The northern sky at the beginning of the monsoon at Harappa in 2500 BC.

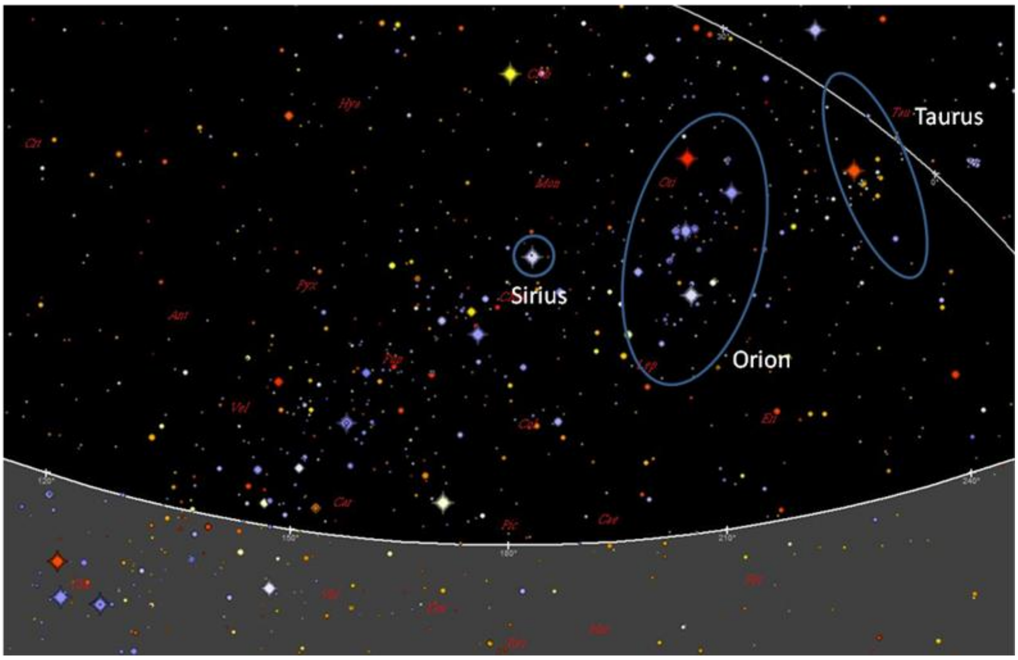

Figure 9: Southern sky at the beginning of the monsoon at Harappa in 2500 BC.

It is also interesting to note that there is a famous seal which depicts a series of images that look similar to some of the constellations. However, it is difficult to prove that this association is a deliberate attempt to depict the sky. If we assume that Arcturus is indeed the star that they worshipped then most of the imagery can be correlated with the brightest stars in the sky at the time of monsoon. This is shown in Figure 10. As can be seen from the left hand image, without the cluttering of the modern division of the sky, most of the stars or asterisms marked by ovals can tentatively be associated with images on the seal.

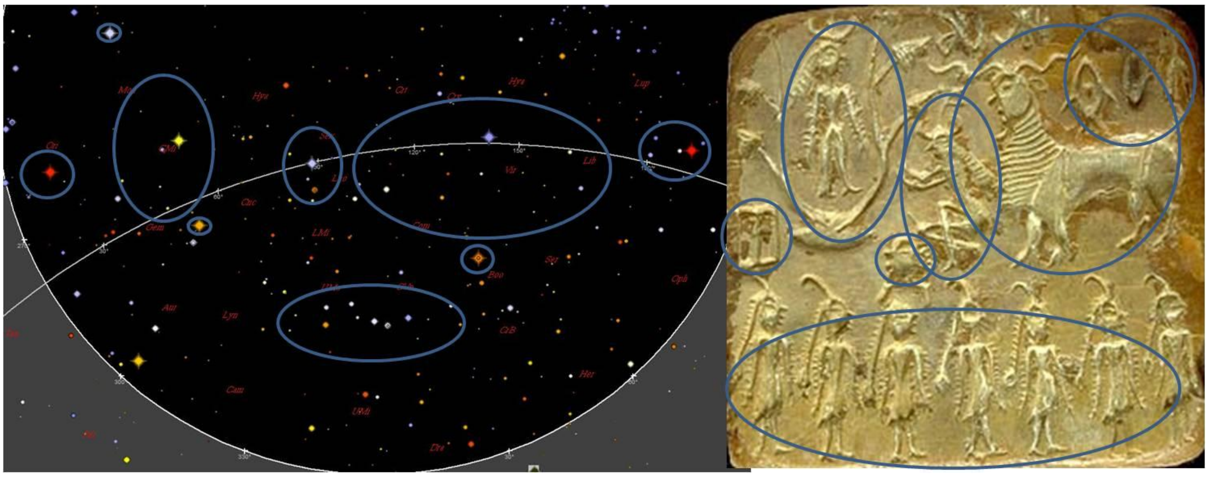

Figure 10: Possible association of the Harappan seal with the night sky at sunset at the onset of the monsoon season.

As a final piece of evidence, we discuss an unusual archaeological monument in Dholavira which is in the shape of the figure ‘8’ (see Figure 11). It is a late Harappan structure that is too small to have been a residence, and its use is currently unknown. However, upon looking out from inside the structure, the doorway points to a direction of 34 degrees west of north, which is exactly the location at which both Arcturus and Vega would set. We therefore suggest that this structure was used to identify the location and time of setting of these important stars.

9 CONCLUSIONS

Based upon astronomical considerations, we argue that in the early part of the peak of Harappan civilisation, the Harappan astronomers must have worshipped Arcturus (*Swati*), but at a later period they switched their focus to Vega (*Abhijit*). We put forward the following arguments for this:

(1) The month of March would have been crucial to them as it would have been the start of the monsoon. At sunset at that time, Arcturus would have been one of the most conspicuous non-circumpolar stars in the less cluttered northern sky, making it a good evening star, while Sirius would have just begun to set.
(2) The Harappans were preoccupied with the northern sky since they predominantly traded with West Asia and the north-western part of the Indian Subcontinent, and the southern sky would not have been uniformly visible from these regions.
(3) Vega would have been the evening star a few weeks later. Hence due to precession when the monsoon shifted to April, Vega would have been the evening star at the beginning of the monsoon.
(4) At that time, in the northern hemisphere the Saptarshi would have been horizontal and parallel to the Earth’ surface, while a handful of other stars would also have been visible, allowing pattern-drawing to aid memory.
(5) This explanation is consistent with the supposedly astronomical seal found at Harappa where seven identical images are shown at the bottom and other animal figures at the top.

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