The Age of Things: Sticks Stones and the Universe
Second Lecture Notes
Matt Hedman
http://cfcp.uchicago.edu/~mmhedman/compton1.html
4/3/2004

Precession, Polaris and the Age of the Pyramids

In the previous lecture, we saw how the calendrical information included in the Mayan texts is a powerful tool for reconstructing their history. Unfortunately, many people were not as fastidious about dating events as the Mayans were, which makes it much harder to arrange these events into a coherent narrative. In these situations, astronomical data can sometimes be extremely useful as a way to locate events in time. For example, it has recently been suggested that the stars can tell us exactly when the Great Pyramids of Egypt were built.

1 A Brief History of Ancient Egypt

In the previous lecture, we saw that the history of Ancient Egypt spans a long time, roughly 3000 years. Unfortunately, the Ancient Egyptians did not have a Mayan style calendar, which counted days from a fixed point deep in the past. In general, the Egyptians counted the years since the last ruler came to the throne. Every time one king died and the next took his place, the count started over again. Such a system is perfectly reasonable and practical. However, it creates obvious problems for historians trying to trace the long history of Egypt.

If we know how many years have elapsed since a certain person became ruler of Egypt, then we can locate the event unambiguously in time if we also know all the people who have ever ruled Egypt and how long each one was on the throne. Unfortunately, although the length of time kings ruled and the sequence of rulers is better known for Egypt than for many ancient civilizations, there are still significant uncertainties

The general outlines of Ancient Egyptian History are well known. Based on the work of an Egyptian priest named Manetho, Egyptian History is divided into about thirty "Dynasties". Each dynasty consists of a sequence of rulers, although it is still not clear what all the rulers in each dynasty had in common. These dynasties are grouped together into the Archaic Period, Old, Middle and New Kingdoms, the Late Period, and three Intermediate Periods (see figure 1). For reference, The Old Kingdom was when the Great Pyramids were built, the Middle Kingdom was when many of the great works of Ancient Egyptian literature were written, and the New Kingdom was when the famous boy-king Tut-ankh-amen lived.

The Late Period, being the most recent period, has the most secure chronology, with connections to Greece, Persia, Mesopotamia and the Levant. During each of the three "Kingdoms", when Egypt had a strong central government, there was a clear sequence of rulers. The length of time each of these rulers was in power is also reasonably well known (although there are still uncertainties), so events within each kingdom can be organized in time relative to each other.

The problem is with the intermediate periods. During these times Egypt's central authority was weak or Egypt was divided among several rulers. Historical data from these periods are sparse and even the number of kings involved is uncertain. The length of time occupied by each of these periods is therefore very uncertain and hinders efforts to assemble a complete picture of Egyptian history.

The Middle and New Kingdoms are reasonably well anchored in time owing to the existence of documents that mention astronomical events. For the sake of time, these documents will not be discussed in the lecture. However, those interested in this subject can read the appendix to these lecture notes to learn more about this subject.

The Old Kingdom poses more of a problem. Documents containing references to useful astronomical events seem to be missing from this time period. Without this information, the age of the Old Kingdom is uncertain by maybe 200 years. As this period is about 4500 years old, this is only a 5% uncertainty in the age. Nevertheless, historians are not satisified with this level of precision.

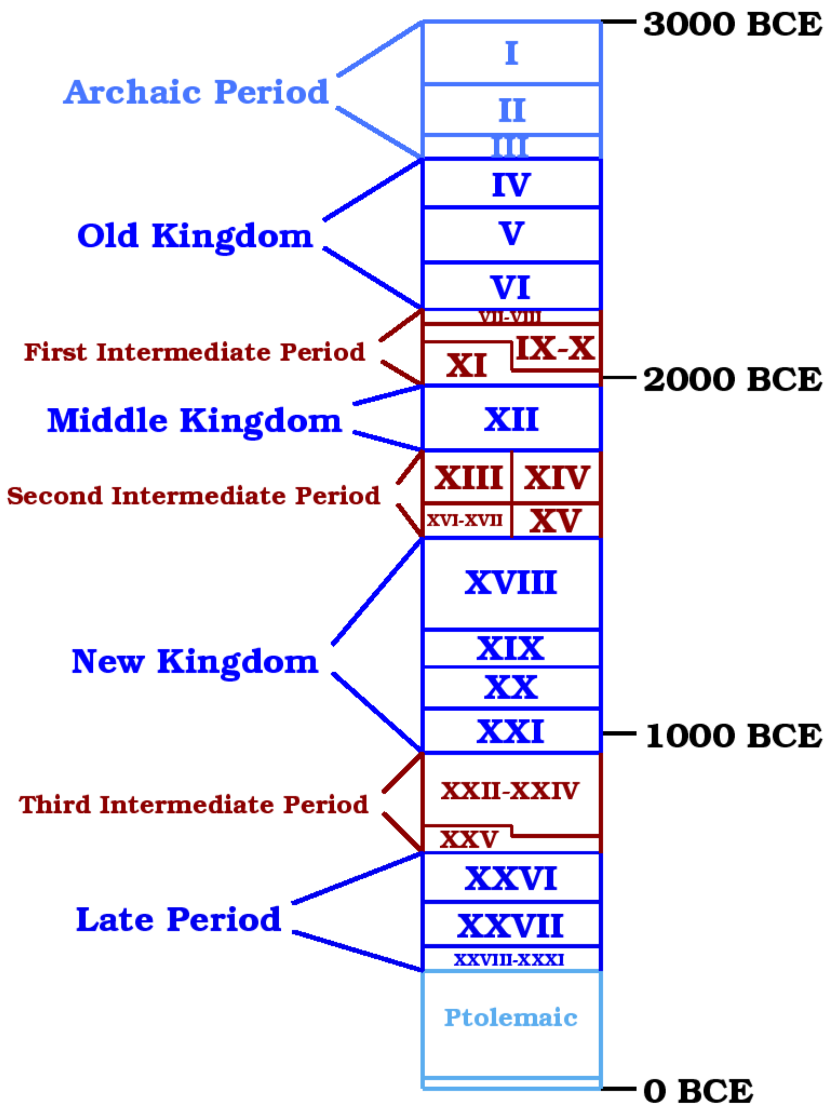

Figure 1: A rough outline of the history of Ancient Egypt. The roman numerals correspond to the Dynasties, while the Kingdoms and Periods are shown at left. The years at the right are only approximate

One hundred years is more than one generation, and is beyond the living memory of most people. Without knowing the age of the Old Kingdom with better precision, it is very difficult to understand the records of the First Intermediate Period or the Early Middle Kingdom, since it is impossible to tell if the last days of the Old Kingdom were "ancient history" or not. This difficulty could be removed if the uncertainty in the age of the Old Kingdom was reduced to a couple of decades.

In 2000, K.E. Spence suggested a way to date the Old Kingdom more precisely. It turns out the greatest monuments of the Old Kingdom, the Pyramids, may hold the key to anchoring the Old Kingdom in time.

2 A Briefer History of Pyramids

The three Pyramids at Giza are only the most spectacular examples of a sequence of monuments spanning many generations. Each of these pyramids is a more-or-less solid mass of stonework that enclosed or covered the burial of a ruler. The forerunner of these structures was built early in the third Dynasty for a ruler named Netjerikhet (later known as Djoser). However, it was during the transition between the Third and Fourth Dynasties that Pyramid-building became a regular industry. The first ruler of the Fourth Dynasty, a man named Snofru, managed to complete three large pyramids during his lifetime (although one pyramid may have been started by his father).

The successors of Snofru are responsible for the pyramids at Giza. These pyramids were built for Khufu, Khafre and Menkaure, who were likely father, son and grandson. Other rulers in this dynasty only ruled for short periods of time, and either barely started construction on their pyramids before they died or constructed smaller tomb structures. The Fifth Dynasty apparently was a new line of rulers that came to power when the Fourth Dynasty failed (The details of the transition between the two dynasties is unclear and shrouded in myth). Several rulers in this new dynasty (including Sahure and Neferirkare) built their pyramids south of Giza, in a place called Abusir. These monuments are a good deal smaller than those in Giza. Even so, they must have been impressive structures for many hundreds of years.

Pyramids continued to be built into the next dynasty, when they included texts on the afterlife of the rulers. These pyramid texts form the oldest corpus of religious literature in Egypt. Pyramids were also built in the Middle Kingdom, although by then they were made of mud-brick instead of stone.

3 A Suspicious Pattern in the Pyramids

The pyramids of the early Old Kingdom are impressive feats of engineering not only because of their sheer bulk but also because of their accurate layout. Although much of the outer layers of stone have been stripped away, various marks at the base of the pyramids are enough to document the care with which these structures were designed.

Of particular interest here is the fact that these pyramids were aligned so their sides face the cardinal directions with errors less than one degree (the two large pyramids at Giza have errors less than one tenth of one degree). The only way to determine true north (or any other cardinal direction) with the required accuracy is to use astronomical observations, but which astronomical object did the Egyptians use? The sun is an obvious candidate, and methods using shadows cast by the sun are quite plausible. However, the pyramids are not perfectly aligned with true north, and the small variations in the orientations of the Pyramids may provide evidence that the Egyptians actually used stars to align their pyramids.

If one takes the pyramids in the order they were built, and plots the deviation in their orientation from true north (which I call the **alignment error**), then one finds the intriguing pattern shown in figure 2. The large pyramids at Giza are the ones closest to true north, while those before and after this time have noticeably larger alignment errors. What is odd, however, is that all of Snofru's pyramids (built before the Giza pyramids) are skewed slightly to the west, while most of the later pyramids are skewed slightly to the east.

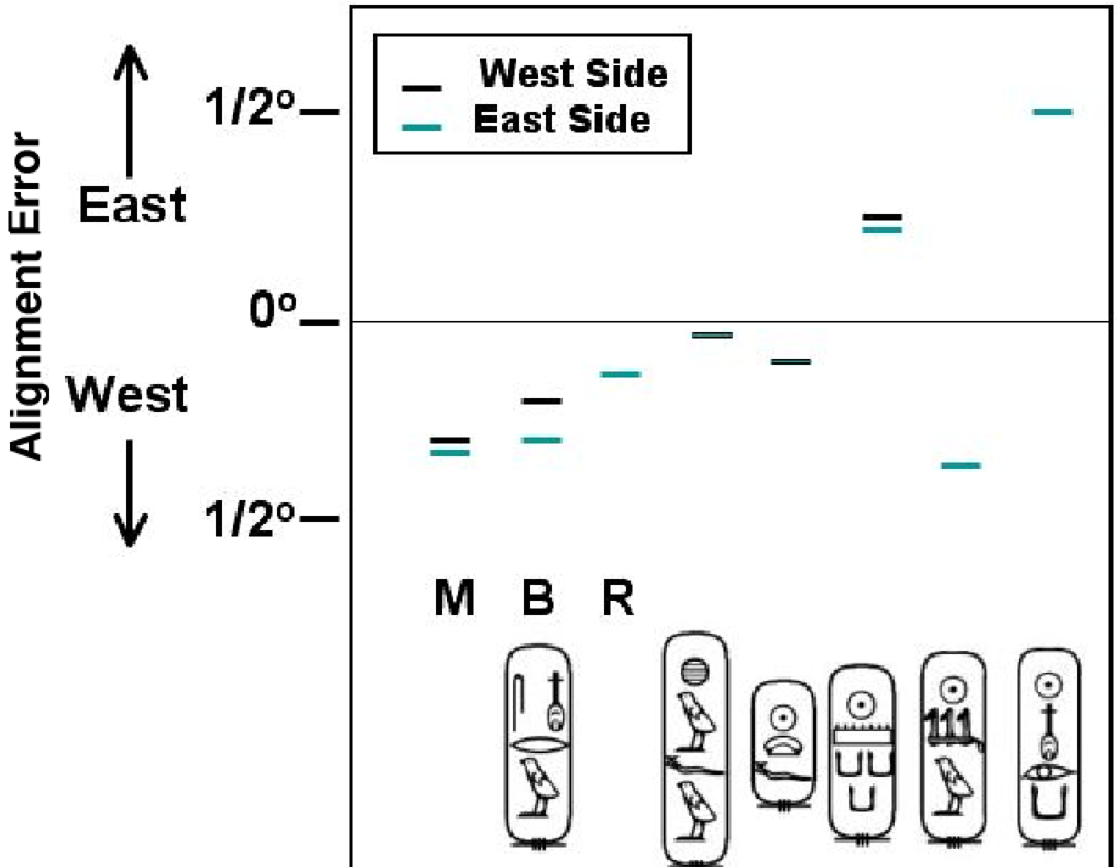

Figure 2: This graph shows the errors in the alignments of the pyramids in the order of their construction (data from Spence 2000). The relevant King's names are given at the bottom (from left to right they are Snofru, Khufu, Khafre, Menkaure, Sahure and Neferirkare). The letters above Snofru's name refer to his three pyramids (Medium, Bent and Red, respectively). For each pyramid, bars indicate the alignment error of the particular pyramid. Note that in general the pyramids start out skewed slightly to the west but with time gradually come to skew eastwards.

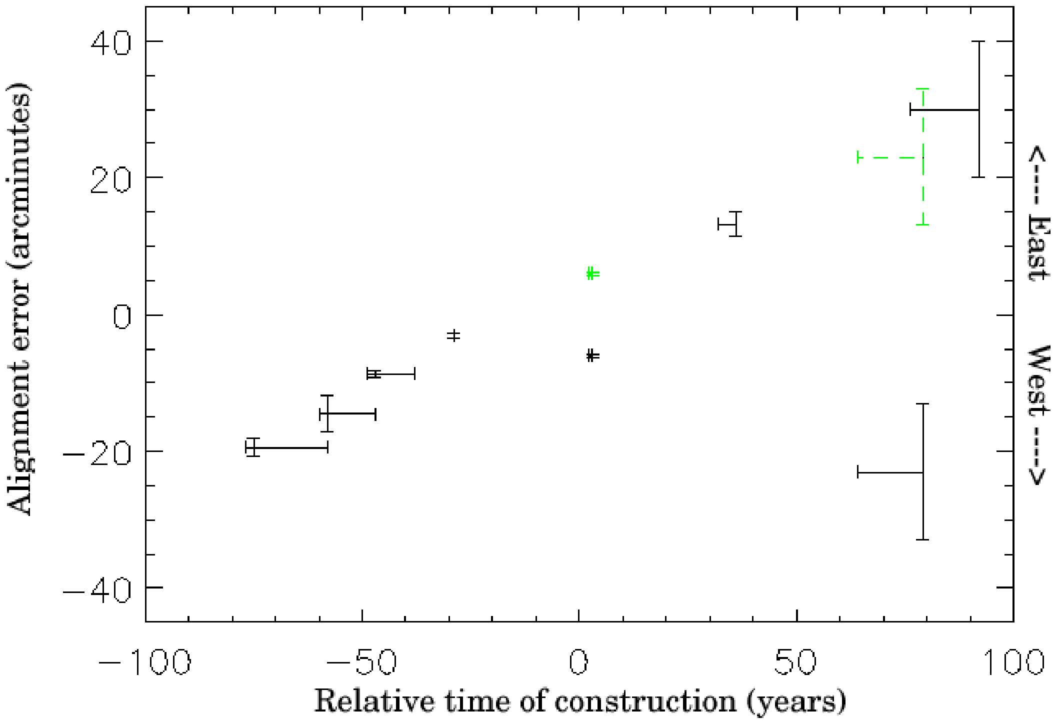

Figure 3: The alignment errors in the pyramids as a function of time (data again from Spence 2000). Here the alignment error is given in arcminutes (60 arcminutes = 1 degree) positive values indicate a skew eastwards, negative a skew westwards. The Black crosses give the measured values and uncertainties of the alignment errors and the times when the pyramids were built relative to each other. Flipping the sign of the alignment error of the two discrepant pyramids gives the gray (green) data points.

This pattern becomes even more suspicious when we include time information, as shown in figure 3. Even then we don't know how many years ago the Pyramids were built, various historical sources give us some idea how long each king ruled. So, assuming each pyramid was laid out as soon as the king came to the throne, we can reasonably estimate how many years elapsed **between** the construction of different pyramids. (For Snofru's three pyramids, additional information is available to determine how much time elapsed between the construction of different pyramids.) We can therefore construct a graph of the alignment error in the pyramids versus time. In this plot, the alignment errors for most of the pyramids seem to fit to a line, and the two pyramids that fall significantly far away from this line, would fall on this line if the sign of their errors are changed from negative (westward) to positive (eastward). (We will see later why flipping the sign of the alignment error might be a reasonable thing to do.)

The final, crucial feature of this pattern is the slope of this line, which gives the rate of change in the orientation of the pyramids per unit time. For these data, this rate is one half of a degree per century. This number is significant because it is close to a fundamental astronomical rate: the rate of precession of the Earth.

In order to understand the significance of this observation and how it can be used to determine the age of the pyramids, we must first know what exactly what I mean by the precession of the Earth. This requires a brief digression into the mechanics of spinning bodies.

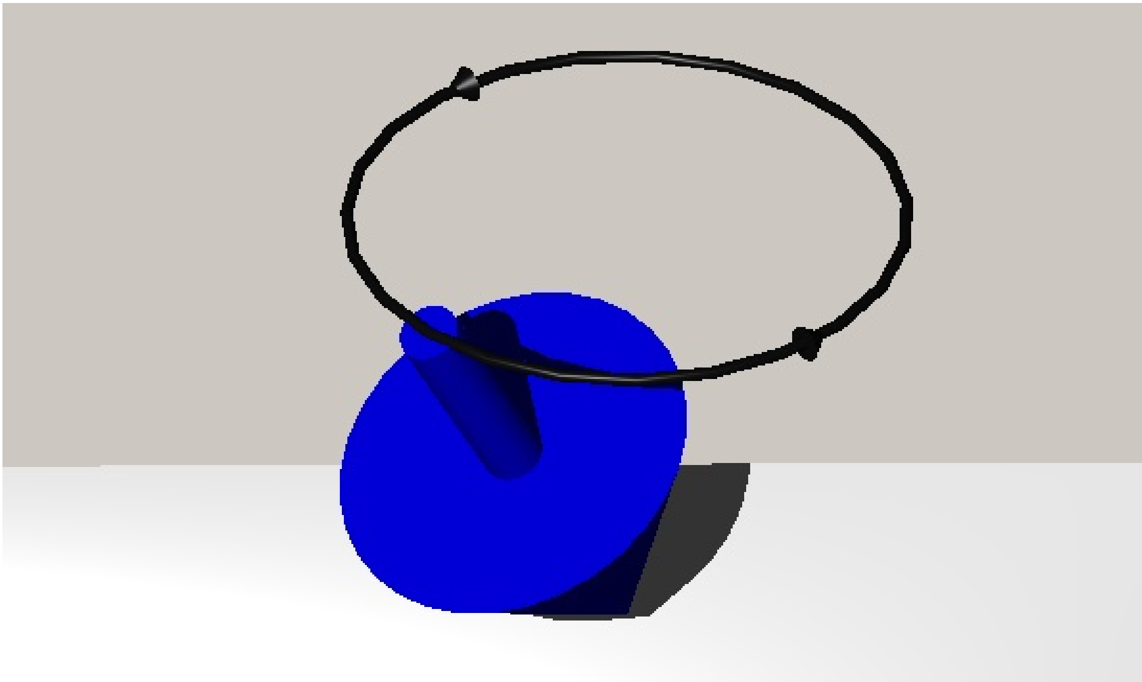

Figure 4: Precession of a spinning top. When a top is tilted, its tip moves in a horizontal central. This is precession. The earth's spin axis moves in a similar way.

4 Spinning Tops and Twisting Pyramids

Precession is a familiar phenomenon in tops or gyroscopes. If the gyroscope is not exactly vertical, then besides spinning rapidly about its axis, the tip of the gyroscope moves slowly in a horizontal circle, as shown in figure 4. This slower motion is the "precession" of the gyroscope, and occurs whenever a rotating object is subject to asymmetric outside forces.

The earth spins on its axis, and it also precesses. The Earth is also slightly non-spherical (wider across the equator than across the poles) and the axis of the earth is not at right angles to the earth-sun line (it is tilted by an angle of about 23°), so the gravitational pull of the sun on the earth is asymmetric. This causes the spin axis to move in a circle just like a gyroscope. Just as the tilt angle of the gyroscope stays the same while it precesses, the earth remains tilted at the same angle during this motion. Precession therefore does not strongly affect how the sun appears to move across the sky.

For those of us living on earth, precession mainly affects the appearance of the night sky. The spin axis of the earth determines the point in the sky that the stars appear to circle around. This point is called the **celestial pole**. Right now, the celestial pole is near Polaris, the "pole star", but this was not always the case (see figure 5). The precession of the earth means the celestial pole moves with respect to the stars in a wide circle centered in the constellation of Draco (see figure 6). Since the spin axis of the earth (and the celestial pole) defines the direction of true north, the movement of the celestial pole with respect to the stars means that the positions of the stars drift with respect to the cardinal directions. For example, right now Polaris gives a reasonably good measure of true north, but 4500 years ago, Polaris could found over 20° east or west of north.

We can calculate how fast the celestial pole moves through the stars from the shape, spin and positions of the sun and the earth. It turns our the pole moves about 1/2° per century with respect to the stars. As the pyramids' orientations change at about this rate, this strongly suggests that the stars, not the sun, was used to align the pyramids. Furthermore, only certain methods of using the stars to define true north will result in orientations that change with time as observed.

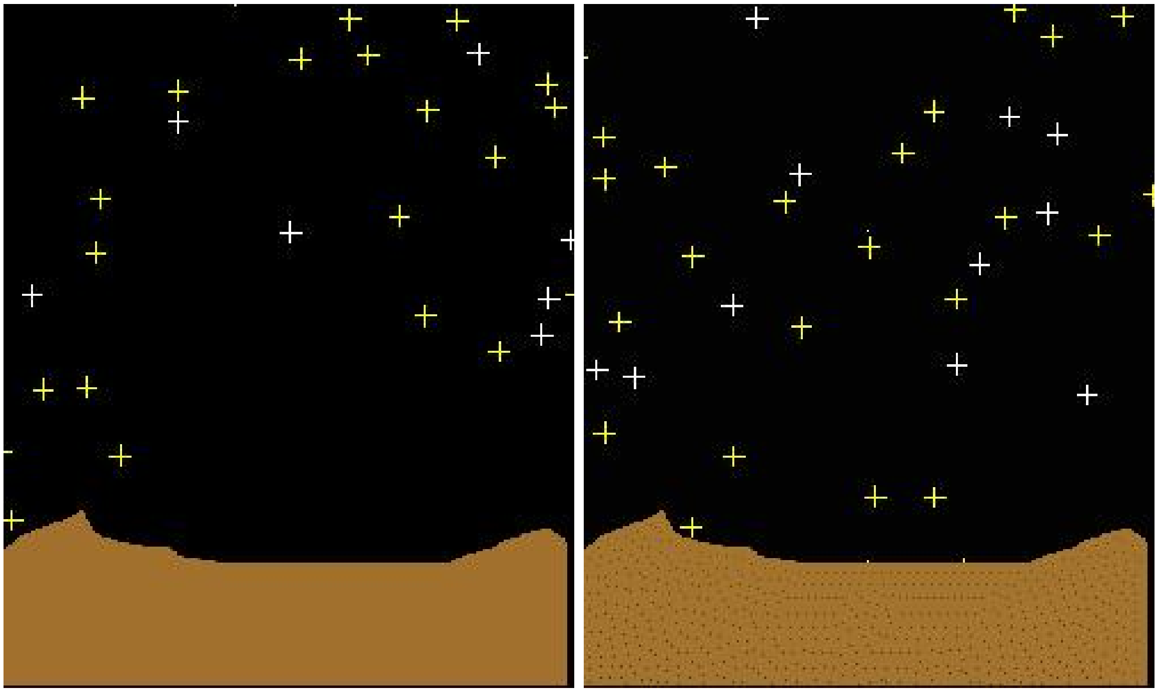

Figure 5: The changing night sky. On the left we see the night sky as it is now. All stars appear to orbit Polaris (near the center of the image). On the left we have the sky as it appeared when the pyramids were built. Note that the stars have changed position, and no bright star was exactly where Polaris is today.

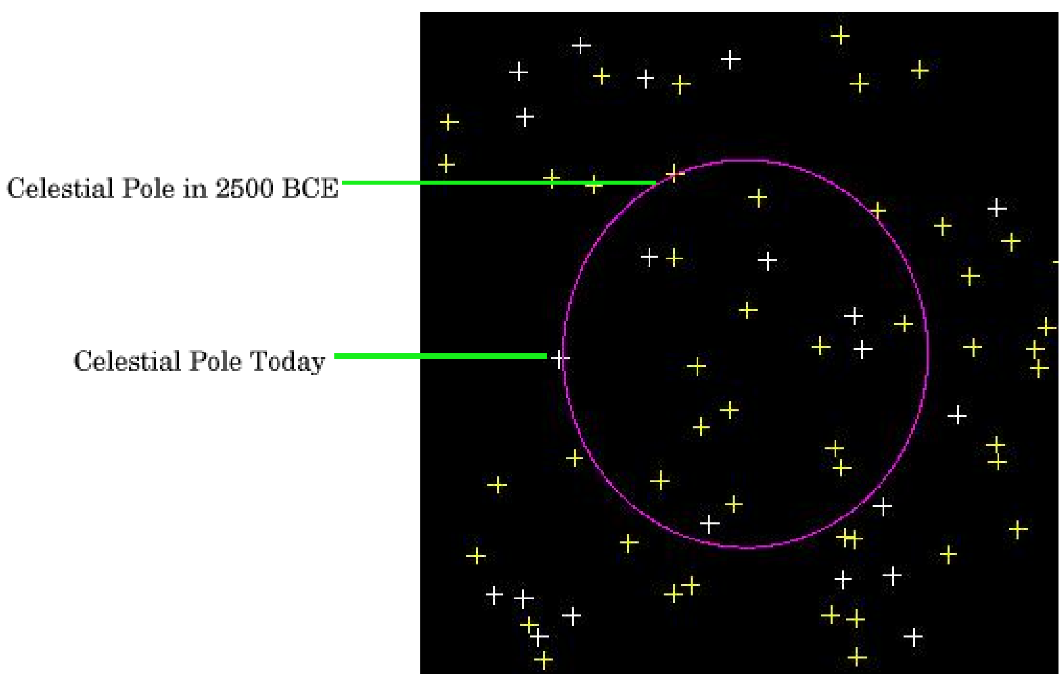

Figure 6: The path of the celestial pole. Due to the precession of the earth, the celestial pole (the point the stars appear to move around) moves around the marked circle once every 26,000 years. For scale, note the Big Dipper in the upper left of the drawing.

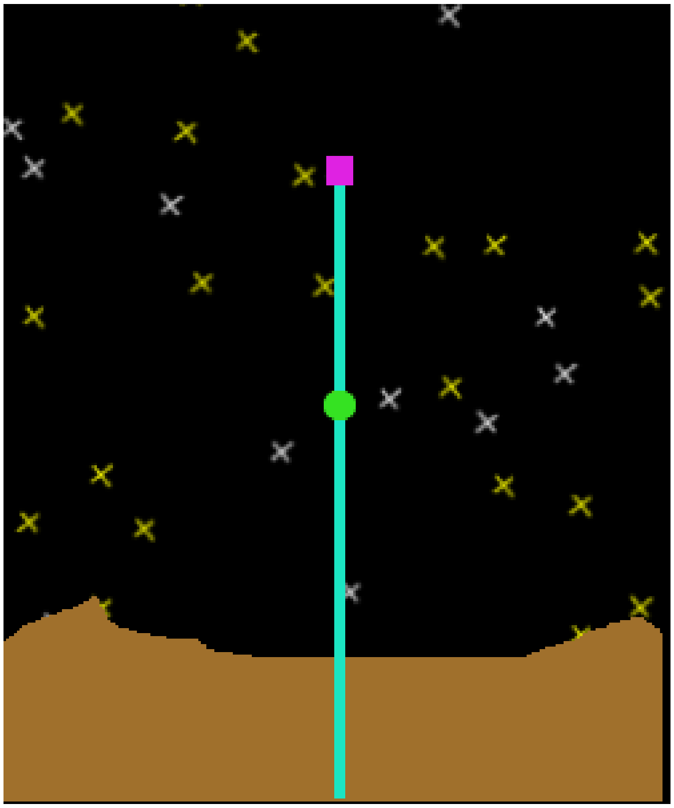

Figure 7: Using two stars to align the pyramid. If the correct pair of stars is chosen (highlighted with the circle and a square), then extrapolating a vertical line connecting the two stars to the ground (for example, with a plumb bob) can provide a good indication of north

4.1 Using the Stars to Align the Pyramids

The connection between the orientation of the pyramids and the precession of the earth has been noticed for some time. What K.E. Spence recently realized was that the slope of the alignment error could not only provide evidence that the Egyptians used stars to align the pyramids, it could also tell us which stars they used, and also exactly when the pyramids were built.

During the range of times when the pyramids were probably built the celestial pole was not near any particularly bright star, so there was no analog of Polaris to indicate the direction of true north. Without a pole star available to them, the Egyptians must have used the stars in some other way to align the pyramids. Whatever this method was, it should depend upon the location of the stars with respect to the celestial pole, so that the precession of the earth will cause the alignment of the pyramids to drift with time.

Spence suggests that the Egyptians used two stars in the northern sky to "point" to the celestial pole and find north. She supposes that when the pyramids were built, there were two stars positioned in the sky such that the line connecting them on the sky passes close to the celestial pole. If there is such a pair of stars, then when the stars are aligned vertically, a vertical line connecting the stars and extended to the ground (i.e. a plumb bob) indicates the direction of true north, as shown in Figure 7.

This suggestion is plausible, in that the proposed method would explain the observed data. The alignment of the pyramids will drift with respect to true north as the celestial pole moves with respect to the line joining the stars. Furthermore, it naturally explains why two pyramids seem to have alignment errors with the "wrong sign" (skewed east instead of west). The sign of the alignment error depends on which of the two stars was higher in the sky when the measurement was made (see

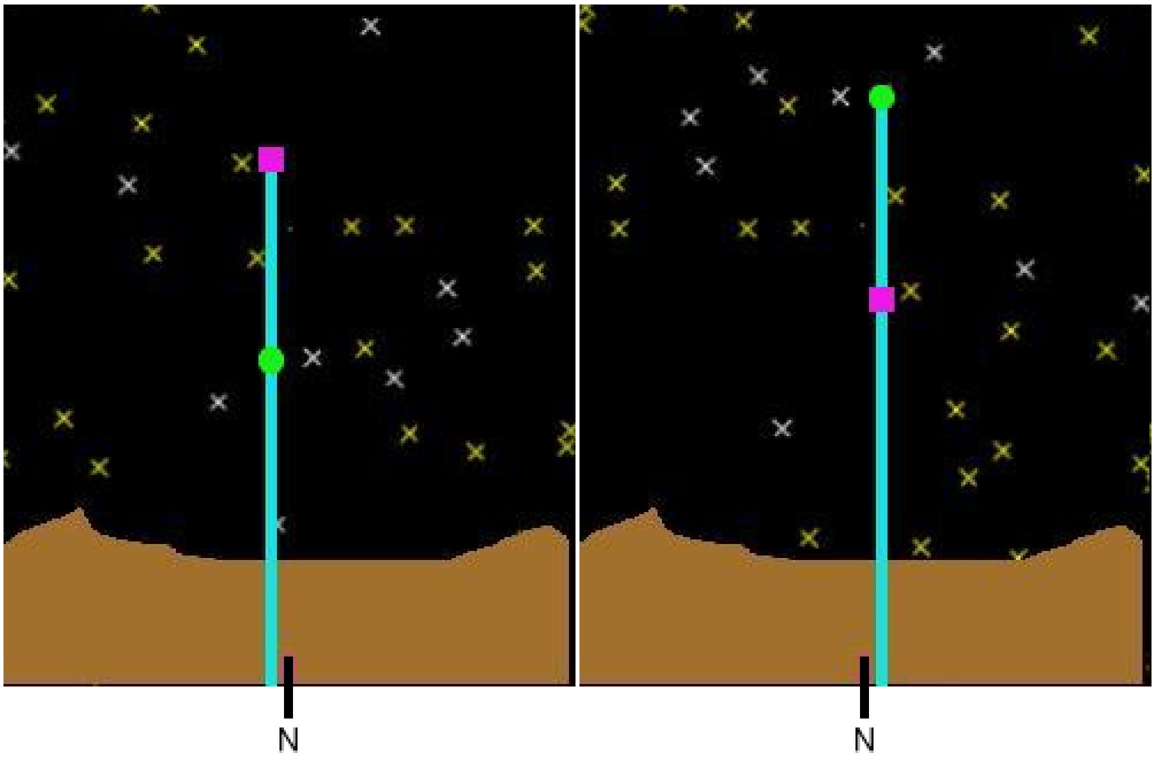

Figure 8: Different errors with the same stars. The same pair of stars (indicated with a circle and a square) are used to determine north, but a different star is higher in the sky in the two plots. The line connecting the stars is used to estimate north (indicated by the short bar at the bottom of the picture). In both cases, there is an error in the measure of north, but in one case the orientation is slightly to the left (west), and in the other it is to the right (east).

Figure 8). This suggests that six of the pyramids were aligned with one star higher in the sky, and the other two were aligned with the other star higher in the sky.

This suggestion also has the attractive feature that it uses northern stars, which we know were very important to the Egyptians. They are mentioned in the pyramid texts, where they were known as the "indestructible stars" because they never went below the horizon or entered the underworld. Since the rulers wanted to be identified with these immortal stars, it would make sense that they used them in aligning their pyramids.

5 Did the Egyptians really do this?

What sets Spence's work apart from other efforts to figure out how pyramids were aligned is that she uses the alignment data to find the particular pair of stars the Egyptians used, which allows her to accurately date the construction of these monuments. By using the alignment data itself, this can be done without knowing exactly how the Egyptians made the measurement or the precise religious significance of different stars in the northern sky.

The celestial pole moves through the sky in a particular direction. The rate at which the alignment error changes with time depends on how the line connecting the stars is oriented with respect to this direction of motion. If the line celestial pole moves along the line connecting the stars, then the alignment error will not change very much, but if the line connecting the stars is almost at right angles to the direction of motion, then the alignment error will change relatively rapidly. Therefore,

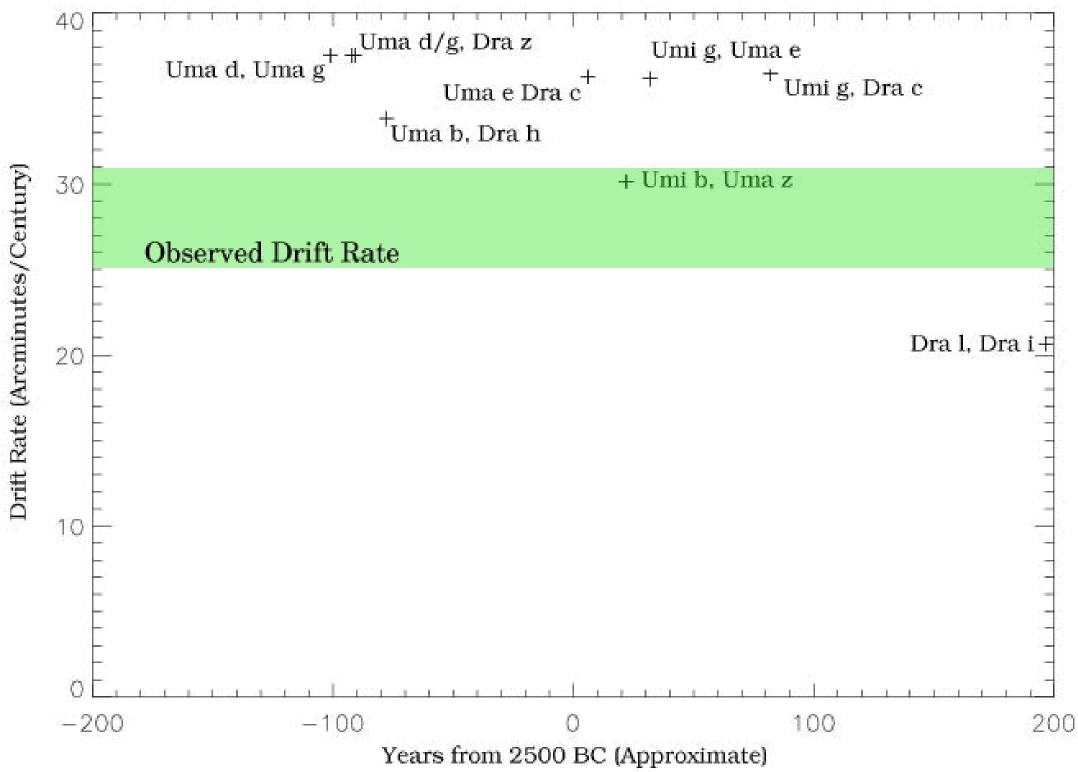

Figure 9: For every possible pair of stars in the northern sky, we compute the rate at which the alignment error should change with time, and the date when the measurement should give exactly true north. These two variables are plotted here. Only nine pairs actually appear in the time range shown here, and only one fits in the range consistent with the observed drift rate (indicated by the shaded bar). This pair is therefore probably the pair that the Egyptians actually used (provided they used this method at all)

we can compare this rate for different pairs of stars to the rate observed in the pyramids and find the best match. Furthermore, if no pair of stars provides a rate close to that observed in the pyramids, then we can rule out this method. This makes this proposal particularly attractive since is rare that a proposal for aligning ancient structures is actually falsifiable.

Spence did not do an exhaustive search of all possible star pairs. However, such a search can be easily done. First, to make the problem tractable, we will consider only the brightest stars (magnitude greater than 4) within 25 degrees of the celestial pole in the year 2500 BCE (a rough estimate of the date when the great pyramids were built based on historical data). There are 18 stars that meet these criteria, which makes for 153 possible pairs. For each pair, it is straightforward to calculate roughly when a line passing through both stars passes through the celestial pole and how fast the alignment error would change with time. Only nine pairs yield lines that go near the celestial pole within 200 years of 2500 BCE, so these are the most reasonable candidate pairs of stars. Now the predicted rate of change in the alignment errors, as shown in Figure 9 for most of these pairs are around 35-40 arcminutes (about 2/3 of a degree) per century, one is about 20 arcminutes (about 1/2 a degree) per century, and one is about 30 arcminutes per century.

Do any of these rates match the rate observed in the pyramids? Given the best estimates of the orientations of the pyramids and the timing of their cons ruction, we obtain rate of 28 arcminutes per century, with an uncertainty of about 3 arcminutes per century. Only one of the above pairs of stars is consistent with this rate. This pair is Mizar (in the Big Dipper) and Kochab (in the Little

Dipper), which are also known as ζ Ursa Majoris and β Ursa Minoris (these are the highlighted stars in figure 7). If the Egyptians did orient the pyramids as Spence proposes, this pair of stars is most likely the one that they used. Knowing which stars they used, we can now figure out exactly how long ago each pyramid was built, because we know exactly when the line connecting these stars passed through the celestial pole. In particular, the great pyramid at Giza would be laid out in 2480 BCE, give or take a few years. This date is fifty years later than the current “best guess” based on historical records, but it is also not wildly unreasonable.

6 Confirming the method: Et tu, Djedefre?

There are two possible ways to further confirm or refute this method of dating the Old Kingdom. One is to refine the measurements of the orientation and relative dates of the pyramids; the other is to determine the orientations of the incomplete pyramids started by various ephemeral rulers of this time, in particular the unfinished pyramid of Djedefre.

Djedefre ruled briefly between Khufu and Khafre (the builders of the two big pyramids at Giza). He began a pyramid in a place called Abu Rowash, north of Giza, but construction had only just begun before it was abandoned (presumably due to the rulers' untimely death). Since Djedefre's pyramid was laid out when the line connecting Kochab and Mizar almost exactly went through the celestial pole, this unfinished monument should be among the most accurately aligned “pyramid” of all. Last year, A French team published the orientation data of the pyramid, and found that it was actually **less** well aligned than any other pyramid from the era (skewed west of north by 0.8 degrees).

This aberrant pyramid clearly fails to support the above proposal for pyramid alignment. However, it does not really falsify it, either. Djedefre chose to be buried far from Giza and the rest of his family, so one might reasonably suggest he also elected to use a different alignment method.

Personally, I think better approach towards refuting the hypothesis is to improve the orientation data of the pyramids that appear to follow the predicted trend. In particular, the errors in the measurements of the fifth dynasty pyramids can probably be reduced significantly. If the refined orientations of these pyramids do not match the predictions, then the support for this proposal is seriously weakened.

Even if this method this method of determining the age of the pyramids turns out to be wrong, it is still an interesting example of how historians attempt to measure age in the absence of complete calendrical information. Combining historical, archaeological and astronomical data clearly allows us to figure out when things happened with great precision (residual uncertainties can be as small as a few years). However, these different streams of information can only be combined productively in rather extraordinary situations, like gigantic monuments aligned with great precision. There are many, less spectacular, objects and events that cry out to be located in time. In the next few lectures, we will discuss Carbon 14 dating, which can measure the age of such modest events as a campfire and tell us when things happened before anyone wrote anything down.

7 Appendix: Of Dog Stars and Leap Years: Dating the Middle and New Kingdoms

The Middle and New Kingdoms are relatively well located in time based on astronomical records and a particularly useful quirk of the Egyptian Calendar. The calendar the Egyptians used to regulate administrative affairs consisted of three seasons, each composed of four months of 30 days, plus 5 extra days to make a total of 365 days in the year.

This year was notionally tied to the seasonal and astronomical events. The names of the three seasons can be loosely translated as “flood”, “growing” and “harvest”. “Flood” refers to an annual event in which the Nile, due to increased rainfall in the Ethiopian highlands, swells and overflows its banks, depositing a new layer of rich soil over the fields. An astronomical event clearly heralded the beginning of this important flood. This was the “heliacal rising” of Sirius.

Sirius is a very bright star in the constellation of Canis Major. For some time during the year this star disappears behind the sun. After about 70 days, it can again be seen low in the sky just before dawn. This event occurs in July, just about when the flood began in Egypt. It is therefore reasonable that the Egyptians considered this event to mark the beginning of the New Year.

However, the Egyptians apparently never used a leap day in the civil calendar, so their year was slightly shorter than the time it takes for the earth to go around the sun (which is about 365.25 days). This meant that the time between heliacal risings of Sirius (tied to the real year) was slightly longer than the time two new years' days in the Egyptian Calendar. The astronomical event therefore occurred earlier and earlier in the year as time went on. Only after about 1456 years would Sirius again appear on the "correct" day.

Although this feature of the calendar could be considered a flaw, it clearly did not pose any serious problem for the administration of Egypt. Furthermore, this quirk has proven to be quite useful for historians. Records from Roman Times tell us that the first day of the Egyptian Calendar and the heliacal rising of Sirius did occur on the same day in year 138 CE. Counting backwards, we can determine that this event also occurred around 1317 BCE and 2773 BCE. We can also calculate for any other year on what day the Heliacal rising of Sirius would actually occur. Therefore, if there is a document that tells us the rising occurred on such-and-such a day, we quickly figure out what year the event occurred in.

Fortunately, there are two such documents, one from the New Kingdom and one from the Middle Kingdom. We will here consider only the Middle Kingdom document, since it is easier to interpret. This document is an unimpressive scrap of papyrus, known by the equally unimpressive name of "Berlin Museum papyrus 10012".

This document records that Sirius appeared on the sixteenth day of the eighth month in the seventh year of a particular king, which is either 226 days late or 139 days early. This could only occur in or around 1872 BCE (other possible dates like 416 BCE and 3328 BCE, can be easily ruled out). Although complications in interpreting this document prevent this date from being nailed down exactly to a single year, it does provide an anchor that fixes the Middle Kingdom reasonably well in time.

8 Further Reading

8.1 Egyptian History

For someone completely unfamiliar with Egyptian History, I recommend starting with:

- Babara Mertz *Temples, Tombs and Hieroglyphics* (1964)

For more detailed general works on Egyptian History, see:

- Peter A. Clayton *Chronicle of the Pharaohs* (Thames and Hudson 1994)
- Ian Shaw *The Oxford History of Ancient Egypt* (Oxford University Press 2000)

8.2 The Pyramids

A good general work on the pyramids is:

- Miroslav Verner *The Pyramids* (Grove Press, 2001)

For more information on how they may have been built, try:

- Dieter Arnold *Building in Egypt* (Oxford University Press 1991)
- Martin Isler *Sticks Stones and Shadows* (University of Oklahoma Press 2001)

8.3 The Physics of Precession

A very good popular work explaining the basic mechanics of precession can be found in:

- Larry Gonick and Art Huffman *Cartoon Guide to Physics* (Harperperennial 1991)

8.4 Precession and the Dating of the Pyramids

The Original Article:

- Kate Spence "Ancient Egyptian Chronology and the Astronomical Orientation of the Pyramids" in *Nature* vol 408 (2000), pp 320

A spirited exchange of letters responding to the article and pointing out a math error in the original analysis are also found in *Nature*, vol 412 (2001) pp 699.

A prior article by S. Haack which also noted precession as an explanation to the pyramid alignment errors:

- Steven C. Haack "The Astronomical Orientation of the Pyramids" in Archaeoastronomy No 7 (1984) pg S119

An article following on Spence's work, that suggests another pair of stars (which are inconsistent with the observed drift rate). It also gives a good discussion of issues involved in stellar alignments:

- Juan Antonio Belmonte "On the Orientation of the Old Kingdom Egyptian Pyramids" in *Archaeoastronomy* no 26 (2001), pg S1

The new measurements of The Djedefre's Pyramid can be found in *BIFAO* vol 102, pg 453.

8.5 Using Sirius to Date the Middle Kingdom

The basic reference of Egyptian Calendars is:

- Richard A Parker *The Calendars of Ancient Egypt* (University of Chicago Press 1950)

For More recent efforts to refine the Dating of the Middle Kingdom, try the references in:

- Leo Depuydt "Sothic Chronology in the Old Kingdom" in *Journal of the American Research Center in Egypt* Vol 37 (2000), pp 167