Some FAQs relating to Measurement of Earth rotation: 720 BC to AD 2015

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Why study ancient eclipse records to determine the length of the day? How can we know these are correctly calibrated?

Historical records of where and when eclipses of the Sun and Moon were seen are the most accurate data for tracing the history of the Earth's rotation before the introduction of telescopic observations after AD 1600. We have analysed records of eclipses from different civilisations - Babylon, China, Greek, Arab - and these independent sources produce coherent results, which means that these must be correctly calibrated regarding dating and places of observation.

Does your paper present the most extensive ever look at the historical, as well as modern, rotation rates of the earth?

The paper presents the most comprehensive assembly and analysis of historical data pertaining to the rotation of the Earth before the introduction of the Atomic Time scale in 1962. The Atomic Time scale is very accurate, but it covers a relatively short time span.

Using simple terminology, please explain how you were able to calculate Earth's rate of rotation using records of ancient and medieval eclipses.

Using the gravitational theories of the orbital motion of the Earth around the Sun and the Moon around the Earth, we can compute where and when eclipses (of the Sun and the Moon) should have been seen in the past, assuming that the Earth's axial rate of rotation has been constant. The historical observations show a consistent discrepancy between these calculations and where and when the eclipses were actually seen. This discrepancy is a measure of how the Earth's rotation has been varying since 720 BC, which is where the extant, reliable and accurate observations of eclipses in ancient civilisations begin.

How would you summarise your findings?

New compilations of records of ancient and medieval eclipses in the period 720 BC to AD 1600, and of lunar occultations of stars in AD 1600 to AD 2015 are analysed to investigate variations in the Earth's rate of rotation. It is found that the rate of rotation departs from uniformity, such that the change in the length of the mean solar day (lod) increases at an average rate of +1.8 milliseconds per century. This is significantly less than the rate predicted on the basis of tidal friction, which is +2.3 milliseconds per century. Besides this linear change in the lod, there are fluctuations about this trend on time-scales of decades to centuries. A power spectral density analysis of fluctuations in the range 2-30 years follows a power law with exponent -1.3, and there is evidence of increased power at a period of 6 years. There is some indication of an oscillation in the lod with a period of roughly 1500 years. Our measurements of the Earth's rotation for the period 720 BC to AD 2015 set firm boundaries for future work on post-glacial rebound and core-mantle coupling which are invoked to explain the departures from tidal friction.

Why is this significant (what does it change about what we thought we knew)?

We knew about tidal-braking slowing down the Earth's rate of rotation. However, observations show that this is not the whole story. Our analysis of the historical records of eclipses shows that there are other geophysical processes at work on a time scale of centuries.

What are occultations?

An occultation is the eclipsing of a star by the Moon in its path as it circles the Earth.

What is tidal friction?

Tidal friction is caused by the tides raised by the attraction of the Moon resisting the Earth's rotation.

What impact does/will this have on our lives?

No practical impact. However, a consequence of this slowing down is that we have to synchronise our clocks (based on Atomic Time) with the Earth's natural clock from time to time by introducing a Leap Second. The next one will be inserted at the end of this year at midnight on 31 December. This decision is made by the **International Earth Rotation and Reference System Service** (IERS, https://www.iers.org), in Paris. The can tell you about this and the relevance of our work to the long term behaviour of the Earth's rotation.

How did you obtain records from as long ago as 720 BC?

We obtained historical, relevant records from historians and translators of ancient texts. For example, the Babylonian tablets, which are written in cuneiform script, are stored in the British Museum, and have been decoded by experts there and elsewhere.

How accurate would those records have been—enough for you rely on them for science?

The quantity we measure from eclipses is the cumulative error in the Earth's 'clock' between now and the historical past. This error amounts to hours. Even though the rate of change in the length of the day is only a few thousandths of a second, about 1 million days have elapsed since the earliest observations that we have analysed (720 BC). The affect in time amounts to hours. So, historical observations measured with an accuracy better than half an hour are useful for our work.

Why are days getting longer at a slower rate than expected?

Braking by tidal friction is the dominant long term force acting to slow down the Earth's rate of rotation. Besides this there are other smaller geophysical mechanisms causing changes in the Earth's rotation. These reduce the effect of tidal braking. They include: deglaciation since the last Ice Age; core-mantle coupling; sea-level changes.

If Delta T is +1.8 ms per century, how much longer will the day be in 2500? Is it possible that glacial melt due to global warming will affect this value?

You mean, if the length of the day (lod) is increasing by 1.8 ms per century. We predict that the lod in 2500 will be about 10 ms longer (see figure 18 extrapolation). However, fluctuations on decade and century time scales make this a bit uncertain. Glacial melting due to human activity could make a small contribution to this by changing mean sea-level, but I am not an expert in this field.

Why is the overall change from 720 BC about 7 hours?

The change in the length of day (lod) of +1.8 ms/cy is actually saying that the acceleration is +1.8 milliseconds per day per century. The epoch (date) from which we measure time in the paper is AD 1825 (not the present day). So, the time span from 720 BC to 1825 is 25.45 centuries (cy) = 25.45 x 36525 days. Thus the **average** change in the lod over that time span is

+1.78 x 25.45 / 2 ms = 22.7 ms = 0.0227 seconds

So the total difference in time (Delta T) over the period 720 BC to 1825 is = 0.0227 x 25.45 x 36525 = 21055 seconds = ~ 6 hours.

Repeating the sum, with the change due only to tidal breaking of +2.3 ms/cy gives is about 7 hours.

At this rate, how long would it take for the day to be one minute longer? And how long would it have taken under the previous assumption?

Over the past 27 centuries, the length of the day has been increasing at the rate of +1.78 ms/cy.

1 min = 60 000 ms.

So, 60 000 / 1.78 = 33 700 centuries = 3.4 million years! A slow process!

Model based on tidal friction of 2.3 ms/cy gives 2.6 million years.

These estimates are approximate, because the geophysical forces operating on the Earth's rotation will not necessarily be constant over such a long period of time. Intervening Ice Ages etc will disrupt these simple extrapolations.

How much longer is the day now than it was in 720 BC?

About 45 ms (thousandths of a second) - see figure 18 of our paper.

Is there a way to calculate how long the day was 65 million years ago, or 2 billion years ago? Or is Delta T too variable to calculate that far back?

The dominant mechanism slowing the rotation of the Earth is tidal braking. The Moon raises tides on the Earth and these cause some drag on the rotating Earth. The amount of this drag depends on the depth of the oceans and seas, and varies with the occurrence of Ice Ages etc. So, it is difficult to extrapolate our result based on 2.5 millennia to 65 million years. Perhaps the day was shorter by between 1/2 hour and 1 hour

Why does the length of the day fluctuate on decadal time scales?

This is because of coupling in the electromagnetic fields between the core and mantle.

Is it possible that this has anything to do with solar activity cycles?

This is contentious. Some have claimed this in the past. We do not see the characteristic 11-yr solar periodicity in our analysis.

Why would the length of the day vary on a quasi-periodic scale of 1500 years? What possible mechanisms could explain this?

This could also be due to core-mantle coupling. You should contact a specialist in this field, e.g. Professor Richard Holme (R.T.Holme@liverpool.ac.uk)

Regarding the following from our paper, what other factors could be causing Earth's rotation to slow down? "Assuming that the measurement of tidal braking in the Earth–Moon–Sun system is secure, our main conclusion is that this mechanism alone does not account for the observed deceleration in rotation over the past 2700 years."

Several geophysical factors have also operated over the past 2700 years. These are:

a. The reduction in the loading from the polar ice caps following the last Ice Age which alters the shape of the Earth slightly and hence its rate of rotation;

b. The electro-magnetic interaction between the core and mantle of the Earth which realigns these, and slightly alters the speed of rotation of the mantle (from where the historical observations were made);

c. Changes in mean sea-level which affects the speed of rotation.

Could human activities be affecting the rate of Earth's rotation? If so, what might those activities be, and is there cause for concern?

Melting of the polar ice caps due to man-made global-warming has a very small effect compared to the overall rate of deglaciation since the last Ice Age

Could the gradual increase in day length, happening due to the deceleration in rotation of Earth, be contributing to climate change?

No.

What future studies do you have planned? The end of your paper seems to suggest that several are in the works. Please explain what they are using simple terminology.

The authors of this paper are basically astronomers. Our main area of research is to gather and analyse historical observations in order to measure the changes in the rate of rotation of the Earth. These results help to set constraints on the geophysical parameters mentioned above. So, the next steps in this area of research will be (and are being) undertaken by geophysicists. As astronomers, with links to the historical nature of the data we have analysed, we can turn invert the problem, and assuming we have an accurate picture of the Earth's rotation, we can investigate historical records of eclipses where the date or place of observation is in doubt. In some cases we should be able to fix either the date and sometimes the place, and this will be of interest to historians wishing to date certain historical events. It would be very useful to uncover more eclipse data from the period AD 1 to AD 400 where we have few data points.

A second source who could comment on our findings - these scientists should be familiar with your work, but someone who did not directly participate in this research.

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Were any of the recorded eclipses particularly beautifully written, or particularly interesting? Or was there anything that stood out at you?

The description in cuneiform script on a clay tablet found at the site of Babylon, and now stored in the British Museum, of a solar eclipse in 136 BC, is particularly fascinating, which is shown on the cover of the Royal Society Proceedings A.

There is also the description given for the 1361 May 5 eclipse in China, which said " … In the time it takes to chew and swallow, the sky became bright again" (see the electronic supplementary material section S3 Commentary on critical eclipses 1362 May 5 (China)).

What other aspects are included in this work

The important work that has been done by experts translating the Babylonian cuneiform script on the thousands of clay tablets stored in the British Museum.

The interdisciplinary nature of our work that brings astronomy to bear on archaeology, history and geophysics.

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