ROBERT R. NEWTON

THE SECULAR ACCELERATION OF THE EARTH'S SPIN

The spin rate of the earth varies constantly. Daily changes are associated with atmospheric winds; long-term changes are related to lunar and solar tidal friction and other slowly changing geophysical parameters. The changes in the earth's spin rate reported here have occurred over periods measured in centuries and are based on observations in historical astronomical texts. The (negative) secular spin acceleration was −19.8 parts per billion per century around the year 600 AD and is now −8.6 parts per billion. These changes in spin rate are due to contributions from tidal friction and from an effect proportional to the square of the time-varying magnetic dipole of the earth. When these contributions are subtracted from the observed acceleration, a residual contribution of +41 parts per billion per century remains that is probably due to variations in the diameter of the earth's core and other geophysical changes.

TIDAL FRICTION

One face of the earth is closer to the moon than its center is, so the moon's gravitation tends to pull that face away from the center. Similarly, the center is closer than the opposite face, so the moon's gravitation tends to pull the center away from the opposite face. As a result, the earth tends to take on an ellipsoidal shape (Fig. 1).

However, the earth does not always present the same face to the moon. Instead, it rotates with respect to the earth-moon line one time in a lunar day, which is about 25 hours. As the earth tries to maintain the ellipsoidal figure that is demanded by the moon's gravitation, each point in it goes up and down twice in a lunar day, giving rise to the lunar tide. There are two tides in a lunar day.

If the tidal motion took place without friction, the tidal bulges would be directly under and directly opposed to the moon (Fig. 1). In that configuration, the gravitational force would point directly along the earth-moon line, and there would be no effect on the rate of the earth's rotation.

In the actual case, there is friction in the tidal motion, with the result shown in Fig. 2. The motion lags the tide-raising force, so that the bulges are displaced in the direction of rotation. The gravitational force is no longer along the earth-moon line, passing through the center of the earth, and the gravitation exerts a torque on the earth. I think the reader can see from the figure that the torque is in the direction opposed to the earth's rotation.

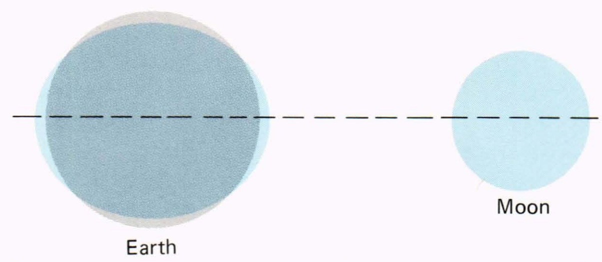

Figure 1—The tide-raising force. Because the moon's gravitation varies with distance, it tends to pull the near side of the earth away from the center and to pull the center away from the far side.

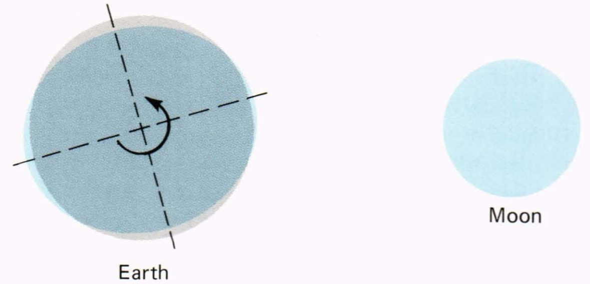

Figure 2—Tidal friction. As the earth moves up and down in response to the tide-raising force, friction causes the motion to lag the force. As a result, a torque tends to slow up the earth's rotation.

In other words, friction in the lunar tide tends to retard the earth's spin.

Of course, there is an equal but opposite torque acting on the moon. The direction of this torque is such that it increases the angular momentum of the moon. However, in order to increase its angular momentum, the moon must move into a larger orbit, in which it has a smaller angular velocity. Therefore, tidal friction decreases both the spin angular velocity of the earth and the orbital angular velocity of the moon.

There is also a solar tide and friction that affects the spin of the earth and its orbital motion around the sun. Although the sun's gravitational effect on the earth is much larger than the moon's, the solar distance is so much greater that the solar tide is actually less than the lunar tide. Friction in the solar tide is large enough that we have to take account of it, but the lunar tide dominates the situation.

Tidal friction is increasing the length of the day by about a millisecond in a century.

THE NEED FOR OLD DATA

By modern astronomical data, I mean data obtained since the introduction into astronomy of the telescope and pendulum clock, which happened about three centuries ago. By old data, I mean data obtained without the use of the telescope and pendulum clock.

The modern data are so accurate that we readily obtain fairly accurate values for the acceleration of the moon and of the earth's spin. Spencer-Jones[1] analyzed a large volume of data and obtained −22 seconds of arc per century per century for the acceleration of the moon. (I will take the second of arc per century per century for the standard unit of the moon's acceleration and will omit the units in the rest of the article.) In a later work (Ref. 2, p. 457), I used some additional data and obtained −28. We may take it that the acceleration of the moon is reasonably well known and that the difference between −22 and −28 indicates the accuracy with which it is known.

No source except tidal friction has been suggested for the acceleration of the moon, so I tentatively take −28 for the lunar acceleration as a measure of lunar tidal friction. By using the known astronomical constants, we can then estimate the effect of lunar tidal friction on the rotation of the earth. From this, in turn, we can use the relations between the astronomical parameters of the sun and moon and estimate the effect of solar tidal friction on the earth's spin acceleration. From these considerations, we find (Ref. 3, p. 219) that the total contribution of tidal friction to the acceleration of the earth's spin is −32.6 parts in 10^9 per century if the lunar acceleration is −28.

In the rest of this article, I will use $\dot{n}_M$ for the lunar acceleration when it is given in the units stated. I will use y for the secular acceleration of the earth's spin when stated in parts in 10^9 per century. Thus, for the contributions from tidal friction, we have $\dot{n}_M = -28$ and $y = -32.6$.

We can also measure y independently. The results[4] are that y is an order of magnitude larger than −32.6, that it changes at irregular intervals that average about 4 years, and that it is about as likely to be positive as negative. The latter fact alone tells us that most of the contribution to y does not come from tidal friction; y would have to be negative if that were so.

That fact also tells us that we must average y over a long time period if we are to learn anything about tidal friction. To get an average that is significant to a size of 1, we must average over about three centuries; this means that the modern data, in spite of their accuracy, can contribute only one data point to our study of tidal friction. To learn more about y, we must have recourse to old data.

Old data are not very accurate, but they do not need to be in order for us to learn something useful about the accelerations. The value of an observation depends on the geocentric angular velocity of the body being observed. The moon has by far the largest angular velocity of any object in the heavens, so that lunar observations are by far the most useful. In fact, for simplicity, I will use only lunar observations in this study.

Old lunar observations give poorly conditioned equations for finding both $\dot{n}_M$ and y, so we cannot determine both of the accelerations with a satisfactory accuracy from the old observations. However, we have a satisfactory estimate of $\dot{n}_M$ from new data, so we will use it in analyzing the old data.

ACCELERATIONS OF THE SUN AND MOON

If the earth's spin is accelerating, the length of the day is not constant, and the day cannot be taken as the unit of time. However, the acceleration of the spin has been known only recently, and all old astronomical observations were made using the day as the unit of time. In the time base in which the day is the unit, the spin is exactly one rotation (with respect to the sun) per day, and it is not accelerating.

In its place we have the acceleration of the sun. If y and hence the spin acceleration are negative, the length of the day is increasing and the number of days in a year is getting smaller. That is, the sun completes one full revolution around the earth in a smaller number of days, so that it appears to be speeding up. Thus, when the day is the unit of length, the sun has a positive acceleration if the value of y is negative.

The system of time in which the day is the unit of time is called solar time. If we adopt a time system in which the sun has no acceleration, that system is called ephemeris time. As far as we know now, the planets do not have any acceleration in ephemeris time, but the moon does. However, its acceleration with respect to ephemeris time, which we have been calling $\dot{n}_M$, is not the same as its acceleration with respect to solar time. In solar time, it has an additional acceleration, positive just like the sun's, that comes from the variation in the length of the day.

Thus the old observations were made using solar time as the time base. This fact tells us how to estimate y from an old observation. We calculate the ephemeris time when the moon had the observed position, using $\dot{n}_M = -28$ in the calculations, which supplies the value of solar time when it had the same position. The difference between ephemeris time and solar time depends on the acceleration y of the earth's spin, and we calculate what value of y leads to the required difference between ephemeris time and solar time.

SOLAR ECLIPSES

When the moon passes between an observer and the sun, part of the sun is eclipsed. But because the moon is relatively close to the earth, its direction at any given moment depends on where the observer is. For some observers, the moon appears to miss the sun completely, and, for others, the moon may appear directly in front of the sun, and the sun may be totally eclipsed.

The distance to the moon is not constant but varies by more than 5 percent from its average value. If the moon is close to the earth when an eclipse occurs, it appears large enough to cover the sun completely, and such an eclipse is called total. If the moon is far from the earth, it is unable to cover the sun totally, and such an eclipse is called annular because a small ring or annulus of the sun is left visible at the height of the eclipse. About half of all eclipses are annular somewhere.

An eclipse does not appear to be the same for all observers. If an observer sees the sun and moon in a straight line at the height of the eclipse, he will see either a total or an annular eclipse. To cover both cases, let us say that he sees a central eclipse. Because the sun and moon are so nearly the same apparent size, an eclipse is central only in a rather narrow zone. For an observer outside this zone, the eclipse is never central and is said to be partial. For an observer far enough away from the central zone, the moon misses the sun entirely and there is no eclipse. A particular eclipse is visible over only a relatively small part of the earth, and observers in most places will not see any eclipse, even though it may be central to some observers.

This fact allows us to estimate y by using statements that an eclipse of known date was seen at a particular place. To simplify the explanation, let us suppose that a record says that an eclipse of known date was total at the particular place. When we calculate the circumstances of the eclipse using $\dot{n}_M = -28$ and $y = 0$, we will find that the eclipse was not total at the specified place. To make it total, we have to rotate the earth without changing the ephemeris time of the eclipse until the observer is brought into the narrow zone within which the eclipse is total.

If the record does not say that the eclipse was total, we do the same thing. If the eclipse was not actually total, we will make an error in the resulting estimate of y; however, the error will average out if we use enough observations. Thus we can use records of partial eclipses as if they were central and not make an error if we have enough records.

A large eclipse, even though not central, is an impressive sight, and the occurrence of eclipses was frequently recorded in old annals, chronicles, and histories. Thus much of the information we use in finding y does not come from astronomy at all but from simple nontechnical sources. In fact, we have more old historical records of eclipses than we have old astronomical observations of the moon.

THE IDENTIFICATION GAME

Unfortunately, the method of using historical records of solar eclipses was misused badly for over a century, during which time it became the most popular method of finding the astronomical accelerations. Since much of the resulting literature on the subject is still widely cited, I want to caution the reader and tell him why the method so often used is wrong.

In using a record that an eclipse was seen at a known place, it is obviously crucial to have the date of the eclipse. Of course, since there are usually only two solar eclipses in a year, and since they will rarely be visible in the same place, we can tolerate an uncertainty of a few years in the historical date of a record and still determine which eclipse could have been seen at the stated place. That is, we can usually determine the date exactly if the record can be dated from historical evidence within a few years.

However, it became popular to use references to eclipses that could not be dated closer than half a century. The date was then "determined" by means of what I call "the identification game," and the resulting record was used to estimate y. The trouble with the procedure is that it was reasoning in a circle.

To play the identification game, the player started by calculating the magnitudes of all eclipses in the possible time frame that could have been seen at the place given in the record. The eclipse with the largest calculated magnitude was taken to be the correct one.

An example of an eclipse that was widely used in the astronomical literature is the so-called "eclipse of Archilochus." Archilochus was a Greek soldier and a poet whose poems can be dated only as being between about -710 and -640. Part of one of his poems is translated in Ref. 5: "Zeus...made night from midday, hiding the light of the shining sun, and sore fear came upon men."

There are several things wrong with using this passage of poetry as an eclipse record in the astronomical literature. For one thing, the passage does not say that the darkness was caused by an eclipse. There is the phenomenon called a dark day, which probably happens at a particular place as often as a central eclipse of the sun does. A dark day is probably caused by weather conditions, and it is just as impressive as an eclipse. However, let us grant that the passage does refer to an eclipse and see where it leads us.

Those who want to use the passage as an eclipse record are forced to assume that Archilochus could have written it only if he had personally witnessed the eclipse. Since one of the characteristics of a poet is his imagination, Archilochus could have imagined the effect of seeing an eclipse if he had ever read or heard about one. The eclipse Archilochus described does not have to be one that was seen at all. Nonetheless, let us assume that the passage does refer to an eclipse that Archilochus actually saw.

The biggest trouble in using an undated passage is that it is necessary to assume a value of y to use in calculating the magnitudes used in dating it, and the identification depends on the value of y used. For example, if we take $y = -19$, we conclude that the eclipse is that of −656 April 15; but if we take $y = -22$, we conclude that the eclipse is the one of −647 April 6.

Now, in using the method, we turn around and use the identification in finding y. Since the identification we make is that of the largest eclipse, the value of y we will get from the identified eclipse is always close to the value of y we assumed in making the identification. Continuing with the eclipse of Archilochus, we get $y = -19.5$ if we take the eclipse to be that of −656 April 15, and we get −22.2 if we take the eclipse to be that of −647 April 6.

Actually, those who used the identification game used it to get the acceleration of the moon with respect to solar time, but the principle is the same. In order to play the identification game, it was necessary to assume a value for the acceleration with respect to solar time; the player then used the identification to find the acceleration he had assumed in the first place. It is this process of reasoning in a circle that I wish to emphasize and not the specific variable used. For simplicity, I will write as if the older work were done in terms of ephemeris time, even though it was done in solar time.

I believe that Sir George Airy, who was the British astronomer royal from 1835-81, was the first person to use the method of reasoning in a circle.[6,7] From then until 1970, when I pointed out the fallacy involved,[8] this method was the most popular, although not the only, one used to find the accelerations.

It is interesting that the value found for y was rather good, even though the method is reasoning in a circle that cannot yield information. The reason for this is that writers before Airy, using valid methods and data, had found a fairly accurate value for the acceleration. The value was assumed in starting the reasoning in a circle, which, in turn, necessarily yielded a value close to the one that was used to start the process.

RESULTS FROM SOLAR ECLIPSES

We can now turn to valid results obtained by using solar eclipses. In two recent works,[2,3] I have analyzed 631 records that tell us that an eclipse of the sun was visible on a known date in a known place. The records fall into three broad classes. One class says that the sun was totally obscured during the eclipse. A second class says that stars (including planets in this context) could be seen during the eclipse but does not say that the eclipse was total. The third class merely says that the eclipse was seen but makes no implication about its magnitude.

For eclipses since about 1000, we can calculate the magnitude of the eclipse with no significant uncertainty. For such records, I have studied the departure of the magnitude from unity, which corresponds to a total eclipse. (The magnitude is the ratio of the part of the solar diameter that is eclipsed to the entire diameter.) For records that explicitly say that the eclipse was total, the magnitude is actually less than unity in a large number of cases, and the deviation from totality is 0.030 on a standard deviation basis. For the records that say the stars could be seen, the corresponding number is 0.051, and for the records that say nothing about the magnitude, the standard deviation is 0.177.

This tells us, among other things, that we may not use the identification game even to find the date of an eclipse, even if we do not go on to find the acceleration from that date. The basic assumption back of the identification game is that the recorded eclipse was the one with the largest magnitude during the possible time period. We see now that this is not necessarily so. For a record that says that the eclipse was so large that stars could be seen, the magnitude can easily be as small as 0.90. With this much range in the magnitude, either date will fit the eclipse of Archilochus with either value of y, and we do not get a unique choice for the date.

In fact, I do not know of any case in which we have successfully identified an eclipse when the record leaves an uncertainty of more than a few years on historical grounds alone.

Returning to the records, the dates range from −719 February 22 to 1567 April 9. I have divided the records into 16 time bins, and I have analyzed the records from each time bin separately. In doing so, I weight each record according to the information it gives about the magnitude; I take the weight to be inversely proportional to the square of the standard deviation of the magnitude that was stated above for each class of record.

The results are shown in Fig. 3, where I give a value and an error bar for y as derived from the records in each time bin. (The year for a plotted point is the average year for the data used in getting that point.) Note that all the points through the year 1005 agree well with each other except for the point at the year 772. Since the year 1000, though, y shows a definite tendency to increase algebraically with time; that is, to decrease in size.

QUANTITATIVE OBSERVATIONS

The results just discussed were obtained from qualitative records that merely say that a certain solar eclipse was visible at a known point. Now we turn to quantitative observations in which some position or phenomenon was measured quantitatively. The old quantitative observations that I have discovered[3] are summarized in Table 1, where the observations have been grouped by type and, within each type, by time bins like those used with the solar eclipses.

The first column in the table gives the average date of the observations within a group, and the second column gives the type of observation. The third

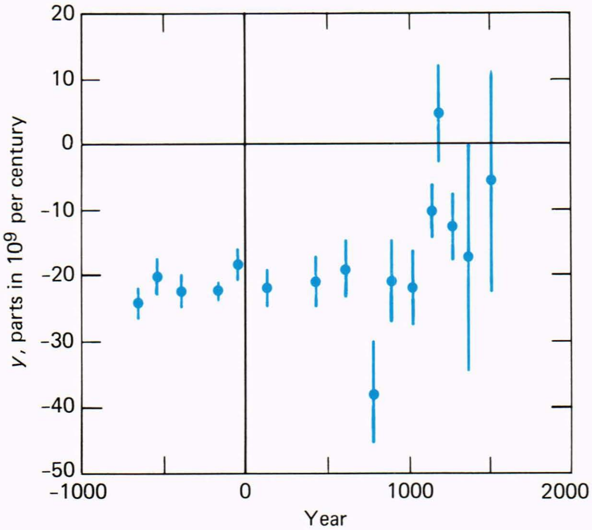

Figure 3—*y* as derived from historical records of solar eclipses. Note the definite tendency of *y* to increase algebraically with time.

Table 1—Quantitative observations.

Average Date	*Type of Observation*	*y*	*σ(y)*
−567	Moonrise and moonset	−10.5	5.8
−567	Lunar conjunctions	−22.6	6.4
−441	Moonrise and moonset	−38.3	7.8
−378	Moonrise and moonset	−22.9	13.3
−378	Lunar conjunctions	−25.5	3.6
−373	Times of lunar eclipses	−22.7	0.4
−321	Time of solar eclipse	−22.1	0.9
−252	Moonrise and moonset	−29.0	6.0
−252	Lunar conjunctions	−19.1	1.3
−250	Moonrise and moonset	−25.1	5.2
−250	Lunar conjunctions	−20.3	2.8
−135	Time of solar eclipse	−22.8	3.3
− 88	Time of solar eclipse	−24.8	2.7
364	Times of solar eclipses	−28.4	5.0
506	Lunar conjunctions	−20.0	4.6
622	Mean lunar elongation	−15.7	6.3
932	Magnitudes of solar eclipses	−19.8	2.8
941	Times of solar eclipses	−16.5	0.8
948	Times of lunar eclipses	−19.7	0.9
979	Lunar eclipse at moonrise	−18.8	2.4
1000	Mean lunar elongation	−19.3	9.2
1092	Time of lunar eclipse	− 5.4	11.7
1221	Magnitude of solar eclipse	− 1.4	25.0
1260	Mean lunar elongation	−46.9	40.0
1333	Mean lunar elongation	−30.9	16.3
1336	Measured lunar longitude	+29.1	21.5
1472	Times of lunar eclipses	−23.2	7.9
1480	Times of solar eclipses	−24.2	7.8
1790	Modern solar data	− 9.1	2.8

column gives the value of *y* inferred from the observations in a group, and the fourth gives the standard deviation of the inferred value. Some of the types of observation need explanation.

The Babylonian month began at sunset on the first day after a new moon that the moon could be seen in the western sky after sunset. The Babylonian astronomers regularly measured the time interval between moonset and sunset on that day. Similarly, near the end of the month, they measured the interval between moonrise and sunrise. Near the full moon, they measured the time intervals of the four possible permutations of moonrise and moonset with sunrise and sunset. Altogether, then, they measured an interval between moonrise or moonset and sunrise or sunset six times each month, weather permitting. The lengths of these intervals form the groups called "moonrise and moonset" in Table 1.

Many astronomers recorded the time when the moon passed a particular star or when it was a given distance from the star. These measurements are the "lunar conjunctions" in Table 1. There is also one measured value of the lunar longitude in the table.

I believe that the times and magnitudes of eclipses are obvious. This leaves the "mean lunar elongation" to explain. We have a number of old tables of the sun and moon from which the values are taken. The tables include tables of the mean positions of the sun and moon, along with tables or formulas for calculating the difference between the mean position and the actual position at any time. The tables of the mean positions had to be based on observations. I have already remarked that only lunar observations are sensitive enough to the accelerations to be useful in this study, so we omit the tables of the sun.

It is clear when we study the methods astronomers used to construct their tables of the moon that they based them on measurements of the lunar elongation, that is, the angular distance of the moon from the sun. Hence, if we subtract the mean position of the sun from that of the moon, we obtain the mean lunar elongation, which represents observation. The date I assign to a value of the mean lunar elongation is the approximate date of the observations used to construct the tables, not the epoch to which the tables are referred.

Table 1 also contains a line called "modern solar data" that I will come back to.

The values and errors in Table 1 are plotted in Fig. 4, except for the modern solar data. When we compare Fig. 4 with Fig. 3, we see that the points in Fig. 4 have more scatter, in spite of being based on quantitative observations. There are two reasons for this. First, old quantitative astronomical observations were not very accurate. Second, there are not as many of the quantitative observations. Figure 4 is based on only 221 observations, while 631 observations were used in drawing Fig. 3.

In spite of the generally larger scatter, the error bars are smaller in Fig. 4 than in Fig. 3 at two stages in history. One is in the −4th century at the height of

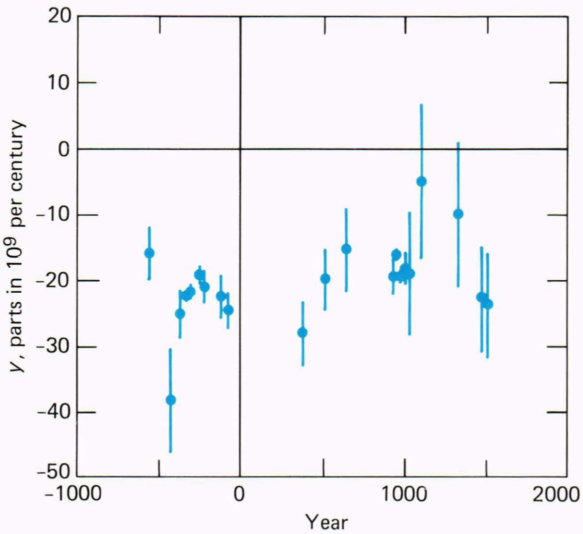

Figure 4—y as derived from quantitative observations that involve the moon. The points show the same tendency to change with time as those in Fig. 3, but the tendency is not as obvious to the eye.

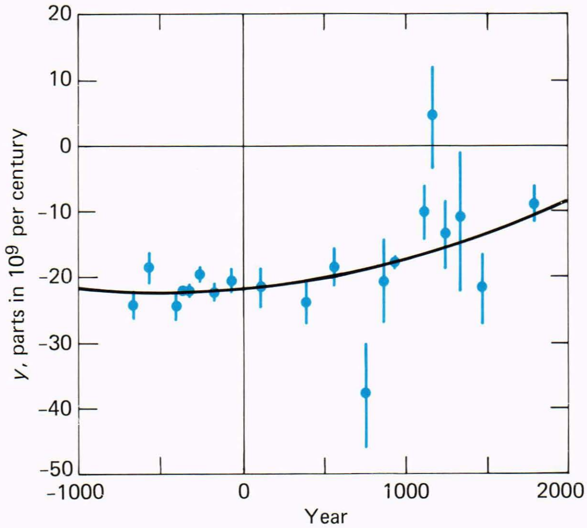

Figure 5—y as derived from all old observations involving the moon, except for the point at the year 1800. That point is derived from modern observations of the sun. The curve is the best-fitting quadratic.

Babylonian astronomy. The other is in the 10th century at the height of Islamic astronomy. At those two stages in history, we have standard deviations in y that are less than 1.

Also in spite of the larger scatter, we can see the same tendency in Fig. 4 as in Fig. 3. That is, y shows a definite tendency to increase algebraically with time. Furthermore, the values of y from the two figures show excellent agreement.

In drawing Fig. 4, I have represented the types of observation that have the same date in Table 1 by a single point. Thus, for example, I have represented both the moonrise and moonset value and the value from lunar conjunctions by the single value -16.0 ± 4.3 for the year -567. I have also represented the four consecutive values with dates from 1221 through 1336 by a single value because of the large standard deviation that each of the individual values has.

COMBINED RESULTS

We are now ready to combine the results from Figs. 3 and 4 to obtain a single set of results from both the qualitative and quantitative observations. In doing so, I have put all the observations of both classes into 19 time bins, with dates ranging from -660 to 1479. For all the observations in a single time bin, I have derived a single estimate of y and an associated standard deviation. The results are plotted in Fig. 5.

In addition, Fig. 5 contains a point at the year 1790. This is from the line for modern solar data in Table 1 and is the value of y derived from modern observations of the sun made with the telescope and pendulum clock. It is

$$y = -9.1 \pm 2.8. \qquad (1)$$

Note that we do not know the value of y as accurately for modern times as we know it for the -4th century from Table 1.

The curve drawn in Fig. 5 is the quadratic function of time that best fits the data. In deriving the best-fitting function, it is desirable to take the origin of time to be at about the center point of the data. I take this to be the year 600. If we let C be the time measured in centuries from the year 600, the best-fitting quadratic is

$$y = -19.86 \pm 0.83 + (0.487 \pm 0.102)\,C + (0.0229 \pm 0.0158)\,C^2. \qquad (2)$$

In the year 600, when $C = 0$, we know y with an uncertainty of less than 1. It is hard to estimate the uncertainty in other years because the uncertainties in the individual coefficients are not independent. However, we see from Table 1 that the uncertainty is less than 1 in the -4th century and in the 10th century, as I have already commented. I think it is fair to say that Eq. 2 represents y with an uncertainty of less than 1 from -600 to 1200.

The estimate of the linear coefficient in Eq. 2 is almost five times its standard deviation, so it is highly significant. There can be little question that y has changed by a large amount within historic times. The estimate of the quadratic coefficient is only about 1½ times its standard deviation, which is not highly significant. That is, a linear variation of y with time fits the data almost as well as a quadratic variation. Nonetheless, there is an independent reason for suspecting a quadratic term, which I will take up in discussing the sources of y. Thus it is probable that the quadratic term is genuine.

The value of y from Eq. 2 has an extremum near the year −460, when its value was about −22.4. Its value for the year 2000 ($C = 14$) is about −8.6. Thus y has changed by a factor of almost three during historic times.

SOURCES OF THE ACCELERATION

Our first problem in looking for sources of the acceleration y is to find a source that can vary significantly with time during a period as short as historic time. All indications are that the oceans have stayed nearly constant during that time. To be sure, there have been slight changes in sea level and in the amount of ice that is interacting with the oceans, but the changes could hardly have changed tidal friction by a factor of three. Thus there is almost surely an important source of y other than tidal friction, even after we smooth out the violent fluctuations that were described near the beginning of this article.

The only important geophysical property of the earth that has changed by an important amount during historic time seems to be its magnetic moment. Smith[9] gives estimates of the magnetic moment from about −1050 to about 1600, and his estimates vary by a factor of two or three during that time.

When we have spoken of the earth's spin acceleration up to this point, we have tacitly meant the angular acceleration of the crust, where the observers lived. This angular acceleration is not necessarily proportional to the time derivative of the earth's total angular momentum, and the angular velocity of the mantle plus crust may not be changing in the same way as the angular velocity of the core, where most of the magnetic field originates.

In other words, the core and mantle may be exchanging angular momentum through the agency of the magnetic field. If they are, the exchange should take place mainly through induced effects, so it should be proportional to the square of the magnetic dipole moment. Accordingly, in Section X.5 of Ref. 3, I squared Smith's values of the dipole moment M and passed a smooth curve through the values. Finally, I fitted the values of y from Fig. 5 to a function of the form $a + bM^2$.[10] The result is

USES FOR ANCIENT ECLIPSE RECORDS

In spite of arguments about the astronomical interpretation of ancient eclipse records, one thing is certain—the more that can be found, the more useful they will be. The sport of wringing information of value in astronomy from historical records has long since been made respectable. It is even tempting to wonder whether the present understanding of supernovae would have been possible without the Chinese record which was recognized, in retrospect, to be a first-hand account of the star from which the Crab nebula was formed (but with a pulsating neutron star left over). The reality of the Maunder sunspot minimum in the early seventeenth century was established (by J. Eddy) by poring over ancient records, this time, to be sure, contemporary astronomical records.

The use of ancient records of solar and lunar eclipses is even longer established. Robert R. Newton begins an elegant paper on the acceleration of the Earth's spin (*Geophys. J. R. Astro. Soc.* **80**, 313-328; 1985) with an account of how Edmund Halley concluded from some observations of lunar eclipses due to Ptolemy that the length of the year had been decreasing. This implied, said Halley, "the necessity of the world's coming to an end, and consequently that it must have had a beginning, which hitherto has not been observed in anything that has been observed in Nature." For his part, Newton wonders how Halley could have come to the conclusion that the Sun was accelerating (when in reality, the opposite is the case) and asks a little wistfully that "if any reader knows the basis on which Halley found the Sun is accelerating, I would appreciate hearing of it."

Since much of Newton's own argument is concerned with demonstrating the pitfalls of using the records of eclipses, he should not be so surprised. The potential value of ancient eclipse data stems from the fact that they provide a nearly exact measurement of the relative longitude of the Sun and Moon (ideally zero for a solar eclipse and 180° for a lunar eclipse) at some distant epoch. In principle, the only changeable elements in this equation are the rate of the Earth's rotation on its axis and the angular velocity of the Moon, which are both affected by their mutual tidal interaction. In practice, so people have been arguing since Halley's time, it should then be possible to calculate from ancient eclipse observations the deceleration of the Earth's spin even as a function of time.

This is precisely what F. R. Stephenson and L. V. Morrison did at the Royal Society's meeting on rotation in the Solar System a year ago (*Phil. Trans. R. Soc.* **A313**, 47; 1984). Their objective, like Newton's now, was to identify the secular change, whatever it may be, in the rate of the Earth's rotation. One obvious complication is that the calculated secular deceleration of the Earth's rotation attributable to tidal action is a mere 2.4 milliarc-seconds per century.

Stephenson and Morrison used a wealth of records, ancient and modern, spanning almost 2,700 years. The earliest data come from Babylonian records, both of solar eclipses and the Moon rising while already eclipsed, with a modest admixture of Chinese information. With the advent of telescopes (and accurate timekeeping) in the past three centuries, occultations of stars by the Moon have become a more accurate way of pinning down the data. One of the striking features of the data set is the poverty of the information available for the medieval period.

The mechanics of Stephenson and Morrison's analysis is outwardly simple. One neat way to describe it is by the difference between Universal Time (UT), astronomical time measured strictly by the Earth's rotation, and Ephemeris

$$y = 8.9 - 0.2268\, M^2. \qquad (3)$$

The term $-0.2268\, M^2$ is the magnetic contribution to y, while the constant 8.9 is the total contribution from all other effects.

Equation 3 gives a very good fit to the data. Further, both Eqs. 2 and 3 require y to have an extremum at about the same time. This is a stronger reason for taking y to be a quadratic function of time than the statistical significance of the quadratic term in Eq. 2.

I calculated near the beginning of this article that the contribution of tidal friction to y, in both the lunar and the solar tides, is -32.6. When we compare this to the constant term in Eq. 3, we see that the total contribution of all sources other than tidal and magnetic must be $+41.5$, which is larger in magnitude than the contribution of tidal friction.

Many writers have suggested contributions to y other than the tidal and the magnetic, but only three show promise of contributing significantly to a value as large as 41.5. The first is a change in the size of the earth's core. As the core grows, it means that dense material migrates from the mantle, where it has a large radius of gyration, to the core, where it has a small radius of gyration. This decreases the earth's moment of inertia and thus increases its angular velocity.

The second is a change in the amount of glaciation. Most glaciers are found at high latitudes, where they have a small radius of gyration. If a glacier melts, in whole or in part, its water runs into the sea and increases sea level all over the earth. This increases the radius of gyration of the earth and decreases its angular velocity.

The third change is cosmological in origin. It seems to be well established that the universe is expanding, which lowers the average density of matter in the universe. According to some theories of gravitation, this causes a change in the constant of gravitation, which, in turn, causes a change in the length of the year without changing the length of the day. Thus the earth's spin velocity would appear to change if the year is the unit of time.

We do not have the basic information that is needed to calculate the contributions that these changes

Time (ET), the smoothed version of UT introduced just over thirty years ago to provide a more uniform measure of the independent variable in the dynamics of the Solar System.

The transformation from one system to the other requires that allowance should be made for the acceleration of the Moon's longitude, supposed to be entirely the consequence of tidal interaction, which was originally taken to be −22.44 arc-seconds per century (and which Stephenson and Morrison think should be 26 in the same units based on observations of the transit of Mercury). Then the difference between UT and ET at any stage should be a measure of the departures of the rate of the Earth's rotation from a fixed value.

The upshot of the Stephenson and Morrison analysis seems to be clear—for the past millennium, the secular change in the length of the day has amounted to 1.4 ms per century, but before that, the rate was greater, more like 2.4 ms per century. It goes without saying that, on the face of things, the more ancient records are in some ways the most telling—the difference between UT and ET increases with the square of the time elapsed.

And of course, the most ancient records do not depend on the timekeeping (if any) used for making the observations; provided that the date of observation is known (or can be calculated or inferred) the equations for the motion of the Sun and the Moon will suffice to fix the time at which an eclipse occurs so long as it is known where the event was seen (and so long as it can fairly be assumed to have been a total eclipse).

Newton's argument sets out to discard eclipse data that are for one reason or another unreliable. He spends more than a page of his printed paper demolishing the case for using as a datum the eclipse whose description is included in a poem by the Greek soldier-poet Archilochus, who is known to have divided his life between two islands in the Aegean. The date is what pérplexes Newton, who concludes that the eclipse described was either that of 6 April, 647 BC or that of 15 April nine years later, and that a suitable choice of values for the acceleration of the Moon's longitude would have made it visible from either island. Both Dicke and Lyttleton, Newton says, used this eclipse in different connections.

Newton has some good clean fun at the expense of what he calls the "identification game" supposed to have been invented by Airey more than a century ago, in which people have been used to assuming a value for the lunar acceleration, using this to calculate past eclipses, using eclipse records to pick on one and using the result to recalculate the lunar acceleration. It is not surprising, Newton says, that the answer is usually not very different from the starting value, for the argument is circular. He is probably right to insist that such data do need careful scrutiny before they are used for serious purposes. The merit of his own analysis is its use of data such as those gathered by the Babylonians for the definition of their calendar consisting of measurements of the angular displacement between the Sun and the Moon at new moon.

Newton may have overlooked the way in which safety can be found in numbers, for within the uncertainties his conclusion is not sharply different from that of Stephenson and Morrison. Briefly, he concludes that the deceleration of the Earth's spin has declined by a factor of about two since 500 BC. He suggests that geomagnetism may provide the explanation. A host of others, such as post-glacial isostacy, would fit the bill. What stands out is that the ancient records, consistent among themselves, still have much more weight in estimating the secular deceleration of the spin than the more accurate modern measurements, befogged as they are by the irregular variations.

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may make to y. All we can say is that the contributions may each be of the order of 10 and that each may be positive.

SUMMARY

We have analyzed 852 observations that involve the moon, with dates ranging from -719 to 1567. We have also analyzed observations of the sun made with the telescope and pendulum clock in modern times. As a result, we have been able to find y, the acceleration of the earth's spin, as a function of time over the past 2700 years.

The result is given in Eq. 2. y has varied quadratically with time, having an extremum about the year -460. Its value at that time was about -22.4 parts in 10^9 per century, and its value at the present time is about -8.6 parts in 10^9 per century.

y contains one important contribution that is produced by, or is at least correlated with, the earth's magnetic field. This contribution accounts for the time dependence of y. The remaining contributions are essentially constant and amount altogether to 8.9 parts in 10^9 per century. One contribution is tidal friction, which amounts to -32.6 parts in 10^9 per century.

This leaves $+41.5$ as the contribution to y from all other sources. At the present time, we do not have the information needed to tell us where that contribution comes from. It probably arises from some unknown mixture of changes in the size of the core, in the amount of glaciation, and in the size of the gravitational constant.

Exciting though it would be, I do not believe that we can contribute to the question of a change in the gravitational constant by studying the earth's spin. There are too many uncertainties in the other sources of the earth's spin acceleration. The question of a changing gravitational constant will probably be settled by the laser ranging of the moon, which has been going on for about a decade. The precision of the data is such that we can probably settle the question in another few decades.

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10 There is one complication. The values of M^2 are instantaneous values, while the values of y are average values of the type I call time-squared averages. By M^2, I actually mean the time-squared average of the square of the dipole moment (see Ref. 3 for details).

THE AUTHOR

ROBERT R. NEWTON is a research physicist who has spent most of his career in fundamental studies of the mechanics of flight of missiles, earth satellites, and spacecraft, and of the motions of the earth, moon, and planets. He was born in Tennessee and earned his B.S. in electrical engineering and M.S. in physics at the University of Tennessee. During World War II, he carried out pioneering studies on the exterior ballistics of rockets and coauthored an authoritative book on the subject. After receiving his Ph.D. in physics from Ohio State University (1946), Dr. Newton joined the Bell Telephone Laboratories, but soon returned to academia as professor of physics, first at the University of Tennessee (1948-55) and then at Tulane University (1955-57). During that period, he continued his research in ballistics.

Dr. Newton joined APL in 1957, in time to contribute to the Laboratory's space program from its inception. In 1959, when the Space Department was formed, Newton became supervisor of the Space Research and Analysis Group (later Branch) and served in that capacity until 1983. He played a vital leadership role, both technical and administrative, in the early days of the Department. He personally led the most difficult theoretical tasks of precisely determining the orbits of earth satellites from Doppler measurements and, from their orbits, determining the geographic variation of the gravitational fine structure of the earth's gravitational field. His skill in difficult analysis and his insistence on the highest standards of rigor and accuracy so improved our knowledge of the earth's gravitational field and of other, time-dependent, forces acting on earth satellites that it soon became possible to predict satellite orbits with high accuracy, an essential requirement for the highly successful Transit satellite navigation system. This pioneering work in both analysis and computation is documented by over 50 publications by Newton and his collaborators, most notably W. H. Guier and S. M. Yionoulis, in the decade 1958-67. In addition to providing the basis for accurate analysis and prediction of satellite orbits, the work was an outstanding contribution to geodesy, improving the knowledge of the shape of the earth—the geoid or equipotential surface—by orders of magnitude.

After the theory and methodology for solving the difficult technical problems of satellite flight had been basically established, Newton (although continuing to direct and supervise improved analysis and computations) turned his personal research attention to basic unsolved problems in geophysics. He first used satellite data to determine the parameters of the earth's crustal tides; this, in turn, led to a study of the secular accelerations of the earth and moon. He found that, for the study of long-term variations in the rotation of the earth and of the orbital motions of the moon and the planets, it was advantageous to use ancient astronomical records, the longer time base more than compensating for the lower precision and accuracy in the ancient observations. So, in the past 18 years, Newton has become a scholar of ancient astronomy and has pioneered in the application of old data in determining the variation in the motions of the earth, the moon, and the other planets over millennia. This work is documented in eight books and numerous shorter publications, culminating in the two-volume work, *The Moon's Acceleration and Its Physical Origins* (1979; 1984).

In the course of these studies, Newton became a superb scientific detective, analyzing both internal and external evidence to determine the probable reliability and accuracy of ancient observations. He discovered numerous errors and discrepancies in both observations and analysis and, most notably, was forced to the conclusion that Claudius Ptolemy had fabricated all the data he claimed to have measured himself and much of the data he attributed to others. That shattering conclusion—for Ptolemy was the most distinguished name in astronomy prior to Copernicus and his work had been thought to be both the summary and epitome of Greek science—was thoroughly documented in *The Crime of Claudius Ptolemy* (1977), Newton's best known and most controversial work. The smashing of an idol was not readily accepted by many historians of science, but the rigor and logic of Newton's analysis are prevailing. (Since this has been Newton's best selling book, one cannot help wondering how many purchasers thought they were acquiring an ancient Egyptian whodunit!)

Newton was a frequent contributor of articles to the *Johns Hopkins APL Technical Digest* and served on the Editorial Board for over two years (1982-84). We shall miss his contributions and his counsel.

Dr. Newton stepped down from his management position in 1983 and retired from the Laboratory at the end of 1984 after seeing through the press his most recent publication, *The Origins of Ptolemy's Astronomical Tables* (1985). We salute his long and exceptionally distinguished career, which has brought great credit to both himself and the Laboratory.