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# Secular Accelerations of the Earth and Moon

## Paleontology, satellites, and ancient astronomy yield accelerations that geophysics cannot yet explain.

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The acceleration of the earth's spin, which is obviously important to astronomy, has also been used extensively to provide information about important geophysical processes. Munk and MacDonald (*1*) have studied particularly those components having a time scale of decades or less. This article will deal with components having a time scale of centuries or more. The average acceleration over an interval of several centuries or longer is usually called the secular acceleration $\dot{\omega}_e$.

The moon also has a secular acceleration, $\dot{n}_M$. As used here, $\dot{n}_M$ means that part of the moon's orbital acceleration coming from dissipative sources and not that part given by the gravitational theory of the solar system. The nature of the available data makes the study of $\dot{\omega}_e$ and of $\dot{n}_M$ inseparable.

Short-period fluctuations in the earth's spin rate are so large that we need data spanning several centuries or longer in order to infer $\dot{\omega}_e$. As a consequence, astronomical data obtained with the telescope and the pendulum clock do not yield an estimate of $\dot{\omega}_e$, although they do yield an estimate of $\dot{n}_M$.

It is helpful to explain a few conventions to be used in this article. $\dot{\omega}_e$ and $\dot{n}_M$ will be calculated with respect to Ephemeris Time, the kind of time kept by the orbital motion of the planets (*2*). Dates will be written in terms of the Julian calendar. The first year of the common era will be written as + 1, the preceding year as 0, and so on. In dates, the year, month, and day will be given in that order. The unit of interval time will be the century. The units of $\dot{n}_M$ will be seconds of arc per century per century. Values of $\dot{\omega}_e$ will be given implicitly by giving $10^9 \times (\dot{\omega}_e/\omega_e)$ in units of reciprocal centuries; $\omega_e$ means the current value of the earth's rate of spin. The units of $\dot{n}_M$ and $\dot{\omega}_e$ will be omitted in the rest of the article.

### Data from Paleontology

Many shell-growing marine organisms lay down their shells or other skeletal structures in small increments which give a wavy or ridgy texture to the skeletal surfaces. The size of the increments and ridges is presumably modulated by any factor that affects growth, such as the seasons.

It was apparently Wells (*3*) who first pointed out the importance of the ridges for geophysics. He observed a nearly periodic modulation on a number of coral shells. He found between 385 and 410 ridges per modulation for Middle Devonian corals. He found 390 ridges from one set of Pennsylvanian specimens and 385 from another, but did not give the limits of the counts. He found that the count for modern specimens "hovers around 360 in the space of a year's growth." He speculated that the ridges represent daily increments, that the modulation is yearly, and hence that the counts give estimates of the number of days in a year at the time when the animal lived. I have not seen any extension of Wells's work, which is potentially of great importance in studying $\dot{\omega}_e$.

Scrutton (*4*) observed a modulation containing about 30 ridges and speculated that this represents a month. If so, the modulation is not caused by tides, which would give two cycles per month. The explanation of a monthly cycle may be that the animals were more interested in the opposite sex during the full moon. Scrutton found a mean of 30.59 ridges per modulation for Middle Devonian specimens, with a range from 29.9 to 31.0.

Clark (*5*) is studying the growth of ridges under known conditions. He finds that they are daily, so we can take Wells's and Scrutton's speculations as being reasonably well established. Clark also finds: "Missing growth lines account for all scatter in the data, so that the maximum, not the average, line count is most representative." It is plausible that we can apply this finding to paleontological species as well, provided that ridges have not been added or lost by damage.

Pannella, MacClintock, and Thompson (*6*) studied samples ranging in age from Upper Cambrian to modern. They find that the number of days per month varied smoothly from about 31½ down to its present value of about 29.53. The number hardly changed between about $3 \times 10^6$ and $0.7 \times 10^6$ centuries ago.

In sum, we can tentatively assume that the number of solar days per synodic month and the number of solar days per tropical year are somewhere between the means and the maxima of the respective ridge counts. In calculations, I shall use these values: 30.7 days per month and 410 days per year for the Middle Devonian about $3.8 \times 10^6$ centuries ago, and 30.2 days per

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month and 398 days per year (I have increased Wells's number in order to allow for missing ridges) for the Pennsylvanian about $3 \times 10^6$ centuries ago.

## Data from Artificial Satellites

The gravitational attraction of the moon distorts the earth and its waters into a prolate spheroid; more complicated components of tidal action can be neglected in this article. The spheroid rotates in space once per sidereal month of about 27.3 days. Every point on earth rises and falls about twice per day (once for each end of the spheroid) as the earth turns with respect to the spheroid. Because of friction, a mass element has its maximum excursion some time after it passes the sublunar meridian, on the average. Thus the axis of the spheroid points east of the moon. The torques exerted by the moon and the spheroid on each other contribute negative amounts to both $\dot{\omega}_e$ and $\dot{n}_M$.

The sun raises a tide which is about 0.4 times as large as the lunar tide and which rotates in space once per year. Friction in the solar tide contributes to $\dot{\omega}_e$ but not to $\dot{n}_M$.

The tidal distortions exert gravitational effects upon satellites near the earth. A careful analysis of the resulting perturbations (*7, 8*) yields estimates of the amplitudes and phases of both solar and lunar tides. From these, it is simple to estimate the amount of tidal friction. The satellite method is currently competitive with other methods of finding global averages of the tidal parameters and may become the leading method in the near future.

Newton (*8*) worked with more data than Kozai (*7*), and his values will be used here. He estimated that the lunar and solar tides contribute $-19.8 \pm 2.8$ and $-2.6 \pm 0.5$, respectively, to $10^9 \times (\dot{\omega}_e/\omega_e)$. He suspected that a bias in his data sample caused an error in his solar result, therefore I shall use only his lunar result here. He also estimated $\dot{n}_M = -20.1 \pm 2.6$ at the present epoch.

## Data from Modern Astronomy

The acceleration of the moon does not seem to have appreciable components with periods less than a century. Hence we can estimate $\dot{n}_M$ from modern astronomical data even if we cannot estimate $\dot{\omega}_e$ from them.

Spencer Jones (*9*) combined ancient observations with modern observations covering an interval from about 1750 to 1930 in order to estimate the orbital accelerations of the sun, the moon, Mercury, and Venus on a solar time base. His estimates relating to the sun and planets let us put the lunar observations on an Ephemeris Time base. The ancient observations cancel out of his final lunar calculations, and in this sense Spencer Jones found $\dot{n}_M$ from modern data alone.

$\dot{n}_M$ and its standard deviation can be estimated from several sets of numbers in Spencer Jones's paper. $\dot{n}_M$ comes out as $-22.44$ for all sets. Its standard deviation depends upon the set, hence there is probably a typographical error in Spencer Jones's paper. The standard deviation is between 1 and 2, and I shall use 1.5. It is reasonable to associate the epoch 1840 with these values.

## Ancient Solar Eclipses

An observation that a solar eclipse was total at a known place is an observation of rather high precision. It is not necessary for the observer to record the time accurately. In almost all cases, we need the time only within a decade in order to identify an eclipse; the place then determines the time with an error of only a few minutes. Thus a person with no astronomical training can make a valuable astronomical observation.

Most of what the 20th-century technical literature has to say about ancient solar eclipse records is wrong. This remarkable situation is the result of three factors.

1) Many studies uncritically accept "records" that were not correct when written.

2) Many statements about the content of an ancient record are not justified by the record.

3) A commonly used method of analysis is fallacious.

The bases for these statements are given in detail in a recent study (*10*) of more than 100 ancient solar eclipse records and about 200 ancient observations of other types. For brevity, I shall refer to this study as *AAO*. Space allows only a brief outline here.

1) Ancient references to large or total solar eclipses seem either "wrong but romantic" or "right but repulsive" (*11*). With a few exceptions, the "right" records come from the annals or chronicles of courts, monasteries, or the like. "Right" records probably outnumber "wrong" records. However, "right" records have not been used much, perhaps because they are, while not really repulsive, at least dull. Ginzel (*12*) in 1899 and *AAO* have apparently made the most extensive use of annals and chronicles for astronomical purposes.

"Wrong but romantic" eclipses come from certain ancient histories and other literature. There are three main subclasses.

*The assimilated eclipse.* People have a tendency to remember the time of one event by relating it to another event. If a chronicler makes an eclipse contemporary or nearly contemporary with another event about a year or less away, and if he makes no great drama of the coincidence, we can reasonably assume unconscious assimilation in his memory and accept the record. If he makes great drama of the coincidence, we should be suspicious.

*The literary eclipse.* By a "literary eclipse" I mean a description of an eclipse inserted into a work of conscious literary invention. The so-called "eclipse of Plutarch" (*13*) is an example of a literary eclipse that has been used in several estimates of the accelerations. The eclipses in *A Connecticut Yankee in King Arthur's Court* and in *King Solomon's Mines* (*14*) are other literary eclipses. I see no reason to believe one more than the others. In fairness, I should point out that probably neither Clemens nor Haggard nor Plutarch meant to deceive us about the occurrence of an eclipse.

*The magical eclipse.* Solar eclipses have a remarkable tendency to happen during battles, at the deaths of great personages, or at the beginnings of great enterprises. By a "magical eclipse" I mean one that is used either as an omen or as a sympathetic magical reaction of nature to human events. The demonstrably false eclipse which Herodotus (*15*) put for dramatic effect at the beginning of Xerxes' campaign against Greece is an archetype of the portentous magical eclipse. The "eclipse of Phlegon" is an archetype of the reaction of nature.

The "eclipse of Phlegon" is a euphemism for the great darkness at the Crucifixion, as told in the Synoptic Gospels. No one has dared use the gospel account directly as a record, presumably from fear of being thought either sacrilegious or unscientific. The "record" of the "eclipse of Phlegon" is actually a passage from the 4th-century patristic writer Eusebius (*16*), who allegedly quoted a lost work by the 2nd-century historian Phlegon, who presumably quoted an unspecified (and still undiscovered) 1st-century source. Phlegon's surviving works indicate a strong liking for marvels. The "eclipse of Phlegon" has often been used as one of the most reliable of ancient eclipse records.

2) The lack of accuracy in discussions of ancient eclipse records is a special case of the general problem of errors in quotation. By a quotation I mean a direct quotation, an indirect quotation, or a statement that someone did or wrote or concluded something. The probability that a technical quotation is correct is discouragingly low. In some of the literature on ancient eclipses, less than half the quotations are correct. Many quotations say the exact opposite of the originals.

For example, Fotheringham (*17*) analyzed a cuneiform text that might have contained a solar eclipse record. He concluded (*17*, p. 124) that "the phenomenon recorded in the Babylonian chronicle was something other than an eclipse, or, if an eclipse, was total in southern Babylonia and not at Babylon itself. . . ." I have seen perhaps a dozen quotations of Fotheringham's conclusion. According to every one, Fotheringham concluded that the text described an eclipse that was total at Babylon.

3) The time of an observation is uncertain in many ancient records. For example, a record may tell us only that a certain person saw an eclipse or that an eclipse occurred during a certain reign. The uncertainty in time is often half a century or more.

When the interval of uncertainty is a decade or less, there is almost always only one possible eclipse. When the interval is several decades, there are almost always two or more possibilities. Whenever there are two or more possibilities, we can play the "identification game" (*AAO*, chap. 3), which has these rules: (i) The player calculates the fraction of the sun that would be eclipsed for each possibility, assuming zero accelerations. (ii) The player tentatively identifies the eclipse as the one for which the fraction is largest. This wording of the rule, or its equivalent, is the one usually assumed in the literature. It conceals from the players the fact that the tentative identification is the one that leads to the smallest estimates of the accelerations. (iii) The player determines whether the tentatively identified eclipse would have been total if the accelerations have "reasonable" values; the player can invent his own definition of "reasonable." (iv) If there are "reasonable" values, the record is called "genuine" and the identification is called "proven." Otherwise, the record is ignored; this happens about half the time or more. (v) Using the "proven" identifications, the player calculates the best estimates of the accelerations.

Most research workers who have estimated accelerations from ancient eclipse records have used the identification game. For example, Fotheringham (*17*) in his famous study started with ten ancient texts. Some texts clearly described solar eclipses, while others described events that may or may not have been solar eclipses. He rejected the "eclipse of Babylon" already mentioned; this left nine. He and others whom he cited used the game to identify five of these. The time intervals used in the game ranged from 35 to 200 years, with a mean of 87 years.

A sixth eclipse, the "eclipse of Phlegon," was identified by a disguised form of the game. There was no possible eclipse during the year stated in the record (*18*), but there was a "reasonable" possibility 3 years away. This possibility was accepted without further exploration. The chance that a "reasonable" possibility will occur within 3 years of a random date has not been calculated, but it must be of the order of 1 in 6.

The most pleasant feature of the identification game is that it can be played with a table of random numbers as readily as with actual records. The quantities to be chosen at random are a place, a date, and a time interval. If the player chooses the interval from a population with a mean of about 40 years, and if he uses a reasonable definition of "reasonable," he will get one "genuine" record with a "proven" identification from about every two random choices. The reader should remember that the average interval used with "records" was 87 years. The rules ensure that the "genuine" records will lead to plausible accelerations and impressively small "data" residuals. Since most of the records used in playing the identification game were probably wrong, the game has in effect been played with random numbers.

## Useful Solar Eclipse Records

For brevity, variables $x$ and $y$, defined by

$$x = \dot{n}_M + 22.44, y = 10^9(\dot{\omega}_e/\omega_e),$$

will frequently be used in the discussion that follows. The result to be expected from any observation is a function of $x$ and $y$; it will be assumed that a linear function is adequate. Thus, comparison of an expected result with a recorded observation yields a relation of the form

$$A_i x + B_i y = Z_i \pm \sigma_{Z_i}$$

for the $i$th observation. $Z_i$ can be called a measurement; $\sigma_{Zi}$ is an estimate of its standard deviation. We can adopt the conventions $B_i = 1$ when $B_i \neq 0$ and $A_i = 1$ when $B_i = 0$.

In *AAO*, I started the analysis of an eclipse record by studying the text, its context, and its historical setting, and I assessed the probability $W_i$ that the record embodied a genuine observation of a large or total eclipse with a known date. I assigned $W_i = 0$ to records like the "eclipses" of Plutarch or Phlegon, I assigned $W_i = 1$ to a note found in an Assyrian court chronicle, and I assigned intermediate values to records with undesirable properties such as being second-hand in the oldest known form. I assigned values to $W_i$ before I calculated the circumstances of the eclipses, and I did not change the values thereafter. The important point about this procedure, which differs significantly from the usual one, is not that the values of $W_i$ are necessarily correct but that errors in them are not biased toward zero accelerations.

The method of calculating $A_i$, $Z_i$, and $\sigma_{Zi}$ will be omitted in this article for lack of space. Two parts of the method should be noted: (i) $\sigma_{Zi}$ contains a contribution based upon the departure from totality allowed by the record (most studies assume, frequently without basis, that the recorded eclipses were total), and (ii) the value used for $\sigma_{Zi}$ was the estimated standard deviation in the usual sense divided by $W_i^{\frac{1}{2}}$.

The records before the year $+500$ for which $\sigma_{Zi}^2 < 50$, and the records after 500 for which $\sigma_{Zi}^2 < 200$, are listed in Table 1 (*19*). The column labeled "Area" gives the general geographical area from which the record came. It is interesting to note that most of the reliable observations before the year 0 are Chinese, although the oldest one is Assyrian. There are only three useful records from classic Greece and two of those are of the same eclipse.

The eclipse of − 762 June 15 is called the eponym canon eclipse, the first listed entry for − 430 August 3 is called the eclipse of Thucydides, and the entry for − 309 August 15 is called the eclipse of Agathocles. These are the only three of the famous "named" eclipses used so much by Fotheringham (*17*) and others which survived the textual and historical criticism in *AAO*. They are also the only three used by Fotheringham that did not require the identification game.

In *AAO*, data before and after 500 were analyzed separately. Eclipses before 500 (*10*, chap. 13) yield the estimates

$$\dot{n}_M = -41.8 \pm 5.3, \; y = -27.7 \pm 3.4. \quad (1)$$

The average date to be associated with these values is about − 360. The variance-covariance matrix for the eclipses after 500 is so nearly infinite that no useful estimate can be formed from them alone.

Estimates in the literature reflect their heavy dependence upon the identification game by being much closer to 0 than the estimates in Eq. 1.

## A Probable Hoax

Ptolemy (*20*) gave the times of two autumnal equinoxes, one vernal equinox, and one summer solstice, which he said were measured with great care. The dates and hours given by Ptolemy are listed in the first two columns of Table 2. Ptolemy gave the times to integral hours, as shown; the hours are presumably in local apparent solar time for Alexandria.

It has long been known that the times in Table 2 are in error by more than a day and there is a large body of literature (*21, 22*) which attempts to explain the errors. It seems to me that there is only one tenable explanation.

Ptolemy used the times in Table 2 to confirm Hipparchus' value of 365 + ¼ − (1/300) days per year in two ways, by comparing his own solstice time with one measured in Athens in − 431 and by comparing his autumnal equinox times with one measured by Hipparchus on Rhodes in − 146. He also used his autumnal equinox time for the year 139 and his vernal equinox time to confirm Hipparchus' value of 178¼ days for the combined length of autumn and winter.

Suppose we fudge the "confirmation" of Hipparchus' results, using the natural choices of starting epochs listed in Table 2. If we keep a precision of 0.1 hour in the computations, we get the date reported by Ptolemy in each case and we get the hours listed in the last column of Table 2. Rounding now yields Ptolemy's exact hours.

The assumption that Ptolemy's times were calculated and not observed does not yield merely smaller discrepancies than other explanations, it yields every relevant digit that Ptolemy wrote down. It is almost inconceivable that measurements could be in error by an average of about 30 hours and still have the exact consistency shown in Table 2 (*23*).

Ptolemy put considerable stress upon the care with which the measurements in his own time were made and upon the confirmation that they gave to Hipparchus' results. For this reason, it does not seem possible to maintain the hypothesis that the calculated values were put down by accident in place of actual measurements. I see no plausible way to avoid the unpleasant conclusion that someone had the deliberate intent to deceive. I also see no way to decide whether Ptolemy was that "someone." For example, Ptolemy might have had an employee or assistant who was assigned the job of measuring the times and who shirked it. If so, Ptolemy was the victim rather than the author of this probable ancient hoax.

Whether Ptolemy's equinox and solstice times were fudged or not, it is clearly inadvisable to use them in astronomical research.

Table 1. Analysis of reports of large solar eclipses.

| Date | Area* | $-A_i$ (cy/″) | $Z_i$ (cy⁻¹) | $W_i$ | $\sigma_{Zi}$ (cy⁻¹) |
|---|---|---|---|---|---|
| −762 June 15 | BA | 0.589 | −18.9 | 1.0 | 2.0 |
| −708 July 17 | C | 0.600 | −15.9 | 0.1 | 3.0 |
| −600 Sept. 20 | C | 0.644 | −18.5 | 0.1 | 2.7 |
| −430 Aug. 3 | M | 0.658 | −12.4 | 1.0 | 1.3 |
| −430 Aug. 3 | M | 0.651 | −11.4 | 0.1 | 6.2 |
| −309 Aug. 15 | M | 0.703 | −16.5 | 0.1 | 6.3 |
| −187 July 17 | C | 0.638 | −19.9 | 1.0 | 2.4 |
| −180 Mar. 4 | C | 0.554 | −17.5 | 1.0 | 3.3 |
| −146 Nov. 10 | C | 0.943 | − 2.7 | 1.0 | 6.1 |
| − 88 Sept. 29 | C | 0.599 | −23.4 | 1.0 | 4.4 |
| − 79 Sept. 20 | C | 0.651 | −13.2 | 1.0 | 2.3 |
| − 27 June 19 | C | 0.654 | −14.2 | 1.0 | 3.5 |
| + 2 Nov. 23 | C | 0.603 | −15.7 | 1.0 | 3.6 |
| 360 Aug. 28 | M | 0.623 | − 5.2 | 0.5 | 4.3 |
| 402 Nov. 11 | E | 0.700 | − 7.5 | 1.0 | 5.0 |
| 418 July 19 | M | 0.510 | −21.0 | 1.0 | 2.6 |
| 447 Dec. 23 | E | 0.708 | −18.3 | 1.0 | 5.2 |
| 484 Jan. 14 | M | 0.536 | −14.0 | 0.5 | 3.6 |
| 538 Feb. 15 | E | 0.640 | + 7.7 | 1.0 | 9.0 |
| 540 June 20 | E | 0.702 | + 0.5 | 1.0 | 10.1 |
| 590 Oct. 4 | M | 0.656 | −14.2 | 1.0 | 4.2 |
| 878 Oct. 29 | B | 0.557 | −14.2 | 1.0 | 10.8 |
| 1133 Aug. 2 | B | 0.656 | + 7.9 | 0.5 | 13.7 |
| 1133 Aug. 2 | B | 0.673 | +16.1 | 0.5 | 11.2 |
| 1241 Oct. 6† | E | 0.635 | − 9.1 | 1.0 | 2.2 |

* B, British; BA, Babylonian-Assyrian; C, Chinese; E, continental European exclusive of Greek; M, eastern Mediterranean, inclusive of Greek, before the Islamic conquests. † This row represents 14 independent reports.

## Other Ancient Data

The maximum fraction of the lunar or solar diameter obscured during an eclipse is called the magnitude of the eclipse. The magnitude of a lunar eclipse does not depend upon $y$, hence lunar eclipse magnitudes have $A_i = 1$, $B_i = 0$. In *AAO* (chap. 9), I found that the precision of the ancient measurements of lunar eclipse magnitudes is about 0.07 (standard deviation). The magnitude changes so slowly with $\dot{n}_M$ that available measurements of such poor precision make no useful contribution to finding the accelerations. We would need perhaps 50 to 100 times as many lunar magnitudes as we now have before they would be statistically significant.

Fotheringham (*24*, see also *AAO*, chap. 9) concluded that lunar eclipse magnitudes are quite useful. He could do so only because he rejected more data than he kept and because he made an error in principle in analyzing those he did use.

In *AAO* (chap. 11), I found that the precision of the ancient magnitude measurements was about the same for solar as for lunar eclipses. This is surprising, since the light contrast is much higher for solar eclipses. The precision was about what we would expect if the ancient astronomers used no instrumental aids and simply tried to divide the diameter by eye (it should be noted that some observers tried to estimate the fraction of the area, rather than of the diameter, that was obscured). Solar eclipse magnitudes are more sensitive to the accelerations than the lunar magnitudes and are marginally useful in estimating them.

In addition to types of observation already mentioned, I used lunar and planetary conjunctions and occultations, times of lunar eclipses, times of solar eclipses, and the mean longitudes at the epoch for the sun and moon from the "Hakemite tables" (see *AAO*, chaps. 2 and 14). [The Hakemite tables were prepared by the Cairo astronomer Ebn Iounis or Ibn Yunis (*25*) in about the year 1000.] Values from astronomical tables should be quite valuable provided that two conditions are met: (i) We must know the mean epoch of the observations used to construct the tables with reasonable accuracy. (ii) Either the epoch of the tables must be close to the mean epoch of the observations or we must know enough about the tables to correct for the epoch difference with high confidence. There are so many questions about the Ptolemaic tables that I did not dare use them in *AAO*. The oldest tables obtained under well-known circumstances that I found are the Hakemite tables.

The results of *AAO* (chap. 14) for different types of observation are listed in Table 3. The lines for large solar eclipses and the columns labeled $Y_i$ and $\sigma_{Yi}$ will be explained later. Since eclipse magnitudes are not being used, the $B_i$ are all unity and have been omitted from Table 3.

Data of all types before 500, including the solar eclipses already used (Eq. 1), lead to the values

$$\dot{n}_M = -41.6 \pm 4.3, \quad 10^9(\dot{\omega}_e/\omega_e) = -27.7 \pm 3.4, \quad (2)$$

with an effective epoch of about − 200. Data after 500 yield

$$\dot{n}_M = -42.3 \pm 6.1, \quad 10^9(\dot{\omega}_e/\omega_e) = -22.5 \pm 3.6, \quad (3)$$

with an effective epoch of about + 1000. The values given in Eq. 2 are dominated by data other than those from solar eclipses. Equations 1 and 2 agree closely because of the basic agreement of various kinds of data, not because the estimates are dominated by the same data.

Agreement between different kinds of data is well shown by the last two columns of Table 3. $Y_i$ means the linear combination $10^9 \times (\dot{\omega}_e/\omega_e) - 0.622\dot{n}_M$. Since $A_i = -0.622$ for several groups of observations, addition of $0.622 \times 22.44$ to $Z_i$ yields $Y_i$ for these groups. For some other types of observations, including large solar eclipses, the values of $A_i$ are close enough to $-0.622$ to let us calculate $Y_i$ with negligible error, using $\dot{n}_M$ from Eqs. 2 and 3. The values of $Y_i$ for large solar eclipses in Table 3 are found by converting $Z_i$ to $Y_i$ and averaging, for four time groups of eclipses.

The values of $Y_i$ show a smooth variation with time. The quadratic form $-2.2 + 0.045(t + 1.98)^2$, in which $t$ is time in centuries from 0, fits the values of $Y_i$ with a standard deviation of 0.7. Table 3 makes it almost certain that there have been large changes in the accelerations within historic times.

## Discussion

In a search for the sources of the accelerations, the part of $\dot{\omega}_e$ that does not arise from tidal friction is more useful than the total $\dot{\omega}_e$. It is straightforward to calculate that the lunar tide contributes $0.935\dot{n}_M$ to $y = 10^9 (\dot{\omega}_e/\omega_e)$. We expect to have an accurate estimate of the contribution from the solar tide

Table 2. Equinox and solstice times reported by Ptolemy, and calculated from Hipparchus' results.

| Time reported by Ptolemy: Date | Hour | Starting epoch: Date | Hour | Hour calculated from Hipparchus' intervals |
|---|---|---|---|---|
| 132 Sept. 25 | 14 | −146 Sept. 27 | 00 | 13.8 |
| 139 Sept. 26 | 07 | −146 Sept. 27 | 00 | 07.2 |
| 140 Mar. 22 | 13 | −146 Sept. 27 | 00 | 13.2 |
| 140 June 25 | 02 | −431 June 27 | 06 | 02.3 |

Table 3. A summary of ancient astronomical data.

| Type | Area* | Approximate epoch (yr) | $A_i$ (cy/″) | $Z_i$ (cy$^{-1}$) | $\sigma_{Zi}$ (cy$^{-1}$) | $Y_i$ (cy$^{-1}$) | $\sigma_{Yi}$ (cy$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Large solar eclipses before − 400 | | −700 | | | | −1.0 | 0.2 |
| Lunar eclipse times | BA | −600 | −0.622 | −16.4 | 0.7 | −2.4 | 0.7 |
| Equinox times | M | −140 | 0 | −23.0 | 5.0 | | |
| Large solar eclipses between − 400 and + 60 | | −140 | | | | −1.9 | 0.2 |
| Lunar occultations and conjunctions | M | −100 | −0.576 | −17.9 | 1.1 | −3.0 | 1.1 |
| Lunar eclipse times | M | − 80 | −0.622 | −14.6 | 0.7 | −0.6 | 0.7 |
| Solar eclipse times | M | +360 | −0.614 | −19.3 | 1.8 | −5.1 | 1.8 |
| Large solar eclipses between 60 and 500 | | 420 | | | | −1.9 | 0.5 |
| Solar eclipse magnitudes | C | 590 | −0.644 | −18.7 | 4.2 | −5.1 | 4.2 |
| Equinox and solstice times | Is | 840 | 0 | −17.0 | 6.0 | | |
| Lunar eclipse times | Is | 900 | −0.622 | − 9.6 | 1.8 | +4.4 | 1.8 |
| Solar eclipse times | Is | 930 | −0.622 | − 9.3 | 0.6 | +4.7 | 0.6 |
| Venus occultations and conjunctions | Is | 930 | 0 | +20.0 | 24.0 | | |
| Solar eclipse magnitudes | Is | 950 | −0.649 | −12.2 | 8.9 | 1.3 | 8.9 |
| Lunar eclipse times | Is | 980 | −0.622 | − 8.9 | 1.5 | 5.1 | 1.5 |
| Longitude of sun at epoch | Is | 1000 | 0 | −25.1 | 5.6 | | |
| Longitude of moon at epoch | Is | 1000 | −0.576 | −11.6 | 0.4 | 3.5 | 0.4 |
| Large solar eclipses between 500 and 1250 | | 1050 | | | | 5.3 | 0.6 |

* BA, Babylonian-Assyrian; C, Chinese; Is, Islamic; M, Mediterranean.

soon. In the meantime, it is adequate to assume here that the solar contribution equals the lunar contribution divided by 4.4 (*26*). Thus $y_{nf}$, the part of $y$ with a nonfrictional origin, is given by

$$y_{nf} = y - 1.147\dot{n}_M. \tag{4}$$

We have estimates of $\dot{n}_M$ and $y$ at two ancient epochs and can estimate $y_{nf}$ at these epochs. We also have estimates of $\dot{n}_M$ at two modern epochs. The estimates of $\dot{n}_M$ and $y_{nf}$ are plotted in Fig. 1 (circles). A linear variation of $\dot{n}_M$ is plausible, but a quadratic variation is better supported. The simplest speculation suggested by the values of $y_{nf}$ is that $y_{nf}$ has been constant within historic times. If $T = t - 19$, the best-fitting parabola and straight line, respectively, are approximately

$$\begin{aligned} \dot{n}_M &= -22 + 3.3T + 0.114T^2, \\ y_{nf} &= +23. \end{aligned} \tag{5}$$

The quadratic form for $Y_i$ that can be derived from Eqs. 4 and 5 fits the values in Table 3 well, but not of course as well as the best-fitting quadratic already given.

Known geophysical mechanisms explain neither the ancient value of $\dot{n}_M$ nor the large change in $\dot{n}_M$ within historic times nor the large value of $y_{nf}$.

$y_{nf}$ can be the result of external torques that tend to change the angular momentum of the earth as well as of internal processes that conserve angular momentum. Coupling of the angular motion of the crust to changes in the magnetic field is conceivable, although no specific mechanism is known, so far as I am aware. From $y_{nf}$ and from estimates of changes in the magnetic field within the past 20 centuries (*27*), we can estimate a charge-to-mass ratio $e/m$ for the currents that give rise to the field. The result is about $10^{-14}$ times $e/m$ for a proton. Fourteen orders of magnitude give considerable freedom to the imagination.

It is controversial whether known mechanisms (*1, 28*) account for the present value of $\dot{n}_M$. Even if they do, they have been almost constant within historic times and hence they cannot explain the ancient values, at least on the basis of present thinking. The amount of change required within historic times may suggest additional mechanisms.

The amount of ice is one quantity that has decreased considerably within historic times (*29*). It is plausible that shelf ice is a good absorber of tidal power. Antarctic ice in particular is

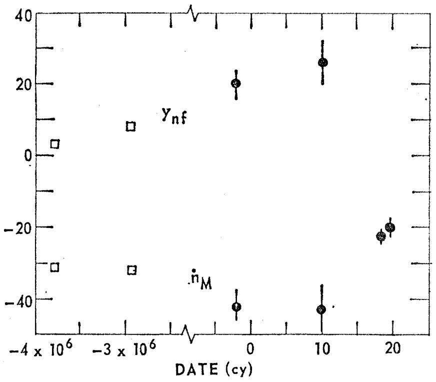


Fig. 1. Secular accelerations within historic and geologic times. $\dot{n}_M$, in the lower part of the figure, denotes the secular acceleration of the moon in units of seconds of arc per century per century ("/cy$^2$). $y_{nf}$, in the upper part of the figure, denotes that part of the secular acceleration $\dot{\omega}_e$ of the earth's spin that does not arise from tidal friction; $y_{nf}$, is in units of parts per $10^9$ centuries. Note the break in the date scale; dates to the right of the break are in centuries and those to the left are in millions of centuries.

exposed to all the major oceans, and it is in a position that favors absorbing large amounts of tidal power. Thus, if ice is indeed an efficient absorber, it is superficially plausible that Antarctic ice is an important cause of tidal dissipation.

At present, tidal power amounts to about $3 \times 10^{12}$ watts. It is possible that an ice shelf with an area of only $10^5$ square kilometers could dissipate this much power without melting. If the speculation is correct, the tides play a significant but not impossible role in the heat balance of Antarctic ice.

Ten centuries ago $y_{nf}$ was (and it still is, so far as we know) as large as the frictional part of $y$ is now. Thus it is not safe to assume, even as a rough approximation, that $\dot{\omega}_e$ depends mostly upon tidal friction.

Contributions to $y_{nf}$ from internal processes probably approach zero when averaged over sufficiently long times. The paleontological data suggest that the average $y_{nf}$ over intervals longer than $10^6$ centuries is considerably smaller than the average over historic times. Because tidal dissipation changes as the 6th or higher power of the earth-moon distance, and because that distance has changed appreciably over geologic times, calculation of $\dot{n}_M$ and $\dot{\omega}_e$ from paleontological data is too lengthy to be described here. The values found for $\dot{n}_M$ and $y_{nf}$ from paleontological data are plotted in Fig. 1 (squares). The values plotted are based upon the following: (i) the data given earlier, (ii) the assumption that lunar tidal friction varies as the 6th power of distance, and (iii) the assumption that other contributions to $\dot{\omega}_e$ have been constant. The values plotted for $\dot{n}_M$ are the present-day values needed to account for the paleontological data, and are not the averages. Since there are no good estimates of the uncertainties in the paleontological data, no uncertainties are given for the corresponding values of $\dot{n}_M$ and $y_{nf}$.

## Summary


The nongravitational part of the moon's orbital acceleration is negative and is due entirely to tidal friction, so far as we know. Ancient astronomical data show with high confidence that the amount of tidal friction 10 centuries ago was about twice what it is now. It is controversial whether mechanisms that have been studied can account for the present amount of tidal friction. They cannot account for the amount found for an epoch 10 centuries ago. Several considerations, including the large changes within historic times, suggest the speculation that much friction originates in the Antarctic ice shelves.

The acceleration of the earth's spin comes from tidal friction and from nonfrictional sources. The average acceleration over the past 10 or 20 centuries is negative. However, the corresponding average of the nonfrictional component is positive and larger than the frictional component is now, and it is possible that the present secular acceleration is positive. Thus it is not safe to assume that the spin acceleration has been governed by tidal friction within historic times.

Paleontological data indicate that the values of tidal friction estimated for historic times, though variable, are typical. They suggest that the historic values of the nonfrictional component of the spin acceleration are somewhat larger than the average over geologic time. This in turn suggests that much of the nonfrictional component comes from internal processes that conserve angular momentum.


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# Sexual Hormones of Achlya and Other Fungi

Molecules controlling genesis of sex organs in two fungi and attraction of sperm in a third are characterized.

A. W. Barksdale

Until last year, a structure could not be assigned to any of several substances known to function as regulators of sexual reproduction in fungi. In 1968, structural formulas were proposed for sirenin, a sperm-attractor in *Allomyces*, and for antheridiol, the initiator of sexual reproduction in *Achlya*, and the agents controlling the formation of gametangia in *Blakeslea trispora* were shown to be trisporic acids B and C, carotenogenic compounds isolated from that fungus in 1964. Sirenin is an oxygenated sesquiterpene, the trisporic acids are terpenoid $C_{18}$ carboxylic acids, and antheridiol is a sterol having the carbon skeleton of stigmasterol.

There is evidence (*1*) for hormonal regulation of sexual reproduction in five other genera: the ascomycetes *Ascobolus* (*2*), *Bombardia* (*3*), and *Saccharomyces* (*4*), and the aquatic oomycetes *Sapromyces* (*5*) and *Dictyuchus* (*6*). In addition, compounds similar or identical to those of *Blakeslea trispora* are involved in sexual reproduction of fungi belonging to five other mucoraceous genera: *Mucor, Phycomyces, Rhizopus, Zygorhynchus*, and *Philobolus* (*7*). These genera are but a small minority among the more than 3500 genera of fungi.

The regulatory substances have been termed hormones because the cells that respond to the regulatory molecules are separated in space from the cells that secrete them. The distance between the two kinds of cells is usually not more than a millimeter or two. For the fungi, their environment—either water or air—serves as a medium through which the hormones diffuse. Like other hormones, those from fungi are highly active in minute quantities. Sirenin, which has a molecular weight of 236, is effective in a concentration of $10^{-10}M$ (23.6 picograms per milliliter). Antheridiol exhibits the same order of activity. Though much more hormone is secreted than is needed to elicit a response, the amount secreted is, nevertheless, very small. This is one reason why so few fungal hormones have been isolated.

## The Water Molds

The genus *Achlya* belongs to a family of aquatic fungi known commonly as water molds. These molds form a major part of the fungous flora of ponds and lakes, where they grow on twigs, fruits, dead insects, and other organic debris fortuitously provided. Members of the genera *Achlya* and *Saprolegnia* are frequently found in association with diseased and moribund fish and fish eggs. Whether they are the primary cause of disease or are only opportunists has not been established. Among species of *Achlya* isolated from infected fish, *A. bisexualis* and *A. flagellata* are the only ones shown able to grow and develop on experimentally wounded fish, a demonstration which seems to implicate these species as agents of disease (*8*).

Water molds are most abundant in shallow, sheltered water where oxygen and food are plentiful. Here vegetative growth is best. The motile, biflagellate asexual spores of water molds may be

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