Reports

Solar Rotation Determined from Thomas Harriot's Sunspot Observations of 1611 to 1613

Abstract. *In 1612 the sun's mean sidereal rotation rate was only 13.3° per day based on a series of 199 unpublished drawings by Harriot. By comparison with the rates in 1625 to 1626 and 1642 to 1644 it appears that the solar rotation was accelerating significantly in the cycles leading up to the Maunder minimum.*

Humanity has long recognized its dependence on the sun's reliability and sought to understand solar behavior. Our knowledge of cyclic and long-term changes derives, of necessity, from comparisons of records over an extended time base. The earliest telescopic observations were at the beginning of the 17th century—just in time to provide some tantalizingly sparse records of sunspots before the sun virtually ceased such activity for 70 years (approximately 1645 to 1715). The diverse effects of this extended minimum of solar activity have only recently been appreciated and the period has been termed the Maunder minimum (*1*). Its cause, however, remains unknown.

Was there unusual solar behavior leading up to this? Eddy *et al.* (*2*) have analyzed sunspot drawings published by Christoph Scheiner (observations of 1625 to 1626) and by Johannes Hevelius (observations from 1642 through 1644). These drawings showed that the rotation of the sun accelerated between Scheiner's records and those of Hevelius, just preceding the Maunder minimum. Most striking is the enhancement of the sun's differential rotation—that is, the dependence of rotation rate on solar latitude—because this speedup appears only for spots within 15° of the equator.

I have extended the determination of solar rotation to the earliest telescopically observed sunspot cycle by analyzing a set of drawings made in England between 1 December 1611 and 18 January 1613 (*3*) by Thomas Harriot (1560 to 1621). These drawings show an anomalously slow rotation, which means that the acceleration up to the Maunder minimum was even more dramatic than was revealed between the observations of Scheiner and those of Hevelius.

It seems clear that Harriot observed the sun directly through the telescope—a hazardous procedure even with the small, imperfect refractors of that day. No actual descriptions have been found of his telescopes or of how the solar drawings were constructed. The drawings exist on loose pages which, like most of Harriot's mathematical and scientific achievements, were never published (*4*), and they lack the finished quality of the Scheiner and Hevelius plates. North (*5*) has painstakingly extracted from Harriot's manuscripts those comments that provide clues to his technique. Various telescopes with magnifications from 8 to 50 were used, those of 10 and 20 power being used most frequently. The telescope mountings, if any, are completely unknown. At magnification 10, Harriot notes (drawing number 26) his field of view to be only two-thirds of the solar disk, and with the 20-power instrument he comments (drawing number 133), "With 20/1 I see a little more than 1/3 of the diameter of the sonne, that is, 11′ or 12′."

In order that measurements of sunspot positions may be compared from drawing to drawing to determine the sun's rotation, it is necessary that a reference direction be available on each drawing. For most of the 199 drawings Harriot indicated with dashed diameters both the vertical direction in his telescope and the ecliptic (see cover). The vertical must have been the primary reference, although it could not have been established with cross hairs since concave oculars were the common design of Harriot's time (*5*), and cross hairs are not reported until the 1630's.

It was apparent to early observers that spots move roughly parallel to the ecliptic, which was an appropriate reference for comparing the drawings. However, the angle between the vertical and the ecliptic varies with date and time of day. Harriot is likely to have used an analog instrument for this calculation (*6*), whereas today the tedium of the spherical trigonometry can be avoided with a digital computer. The latter being more accurate, there is no reason to rely on Harriot's ecliptic. Nonetheless, the vertical-to-ecliptic angle was measured in each of the drawings (148 out of the 180 used) where it appeared. On the average these are only 3° too large (errors range from −6° to +15°) for the recorded time of the drawing.

The configuration of spots with respect to the vertical had to be estimated quickly because of the changing vertical-to-ecliptic angle—in some cases more than 2° within the 1/4-hour accuracy to which Harriot usually recorded time (and which he wrote as a fraction). The problems and uncertainties of timekeeping in Harriot's day must be judged here, not with regard to the minor rotation of the sun on its axis during the uncertainty interval, but with regard to the turning of the image in relation to the vertical. It must have been a task of some difficulty to search visually for spots on the bright solar disk, only a part of which could be seen in the field of view, and rapidly transfer their estimated positions to a drawing.

Harriot generally made his observations shortly after sunrise. With the sun near the horizon the vertical was probably easier to estimate and the sun could be viewed from a more comfortable position. But, of overshadowing importance was the dimming of the solar image afforded by atmospheric extinction at low celestial altitudes. Almost invariably Harriot's commentary first notes the cloud conditions (a virtue of the London climate in this instance) and the brightness of the sun. Of the 180 drawings measured in this study, the mean astronomical altitude was 11°; but 70 percent were lower than this, the mode being 3°.

A total of 690 observations of spot positions were measured, representing 146 different spots—an average of 4.7 observations per spot. I attempted to include all spots that appeared on more than three drawings. The largest number of appearances was ten. By the end of 1612 Harriot was observing the sun less often; so, beginning with drawing 180, I included some 14 spots that were recorded only twice (however, the mean time between these records was 4.6 days). In the calculation of rotation rate the spots were weighted by the number of observations.

The drawings were digitized on a Bendix Datagrid, which gave a measurement precision at least an order of magnitude better than the accuracy of the plotted spot positions. This is judged

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from two instances (12 February and 11 August) in which Harriot recopied his drawings, perhaps because of spilling or smudging ink on the pages. A comparison of the duplicated drawings showed that spot positions differed on the average by 0.03 (expressed as a fraction of the drawing's radius). In this context it should be remarked that the extant Harriot solar drawings are almost certainly fair copies of sketches that he made at the telescope (*5*).

Chosen as fiducial points for each drawing were the center of the sun's circle (usually a visible dot at the intersection of the vertical and the ecliptic) and the end points of the vertical diameter. To provide a first-order correction for x-y scale distortions on the photocopies, each spot's x and y coordinates were expressed as fractions of the horizontal and vertical radii, respectively. This necessitated measurements of the horizontal diameters, which were found to differ from the vertical diameters by an average of somewhat less than 1 percent.

A coordinate rotation from the horizontal to the ecliptic was followed by a transformation from rectilinear to heliocentric spherical coordinates. At this point it was easy to allow for the perspective change resulting from the earth's orbital motion around the sun. Since the longitude of the sun at the time of the drawing is known (*7*), the ecliptic longitude of each spot could be expressed with respect to the vernal equinox. Thus, sidereal (not synodic) rotation rates automatically resulted without approximations in the later calculations.

I made various attempts to determine the solar rotational pole from the Harriot data, using spots individually and collectively. However, the uncertainties were too large to justify choosing a pole that differed from that predicted for 1612 by the widely used Carrington (*8*) elements. The latitude and longitude (*9*) with respect to this pole were computed for each observation of a particular spot. The regression line of longitude on time gave the rotation rate for that spot.

Latitudes ranged from 2° to 38°, with a weighted average absolute value of 16.7° ± 6.8° (standard deviation). This suggests (*10*) that Harriot was observing near the time of sunspot maximum, and the increasing number of spots through 1612 suggests that the peak was not yet passed.

The weighted mean sidereal rotation rate was 13.265° ± 0.096° (standard error of the mean) per day. The corresponding mean synodic rate of 12.28° per day is obtained by subtracting the earth's mean rate of orbital revolution, 0.986° per day.

This rotation is notably slower than that calculated for either the Hevelius or the Scheiner data. The comparison is best seen in Fig. 1, where the rotation is plotted as a function of latitude. The curve for 1625 to 1626 approximates the sun's average rotation in the first half of the 20th century (*11*) except for the speedup at latitudes greater than 25°. Differential rotation from Harriot's data lags behind about 1° per day, like an exaggerated mimic of the Scheiner data, even to the extent of returning to equatorial speeds at its highest latitudes.

More complete statistics of the 1612 differential rotation are given in Table 1. The startlingly large reversal to rapid rotation at high latitudes is seen there to derive from only five spots. Were all spots above 25° latitude averaged together, the mean rotation would be 13.05° per day at mean latitude 28.2°, and no reversal would appear in the plot. To further illustrate the extent of uncertainties arising from the statistically small sample, I have included in Table 1 the rates computed about the pole predicted for 1612 from the recent determination by Wöhl (*12*). This shows the effect of a small change (0.5°) in the assumed polar location. The minor differences result primarily from shifting some of the spots into different latitude zones. The mean rate for all spots is changed by less than 0.01° per day.

Another check on the validity of the results is to avoid spot observations near the limb, where the longitude uncertainty is greater because of foreshortening. If only those spots observed within 40° of longitude from the central

Table 1. Differential solar rotation in the year 1612 about a pole defined by i = 7°15′ = inclination of the solar equator to the ecliptic and Ω = 70°21′ = longitude of the ascending node (intersection of equator and ecliptic) (*8*). Mean values were computed from the spots in the latitude intervals (north and south combined) with each spot weighted by the number of times it was observed. The values in parentheses, included for comparison, are based on a pole at i = 6°46′ and Ω = 71°14′ (*12*).

Latitude interval (degrees)	Number of different spots	Total number of spot observations	Mean latitude (degrees)	Mean sidereal rotation rate ± standard error of the mean (degrees per day)
30 to 38	5 (5)	15 (15)	33.0 (32.9)	13.76 ± 0.54 (13.75 ± 0.52)
25 to 30	17 (17)	83 (83)	27.3 (27.3)	12.92 ± 0.39 (12.92 ± 0.39)
20 to 25	22 (22)	103 (103)	22.2 (22.3)	13.11 ± 0.31 (13.11 ± 0.31)
15 to 20	36 (38)	187 (195)	17.3 (17.3)	13.28 ± 0.19 (13.21 ± 0.19)
10 to 15	41 (39)	189 (182)	12.9 (12.9)	13.28 ± 0.14 (13.42 ± 0.14)
5 to 10	23 (22)	105 (99)	7.4 (7.5)	13.51 ± 0.18 (13.44 ± 0.18)
0 to 5	2 (3)	8 (13)	1.8 (3.3)	13.76 ± 0.18 (13.75 ± 0.11)
All spots	146 (146)	690 (690)	16.7 (16.8)	13.26 ± 0.10 (13.27 ± 0.10)

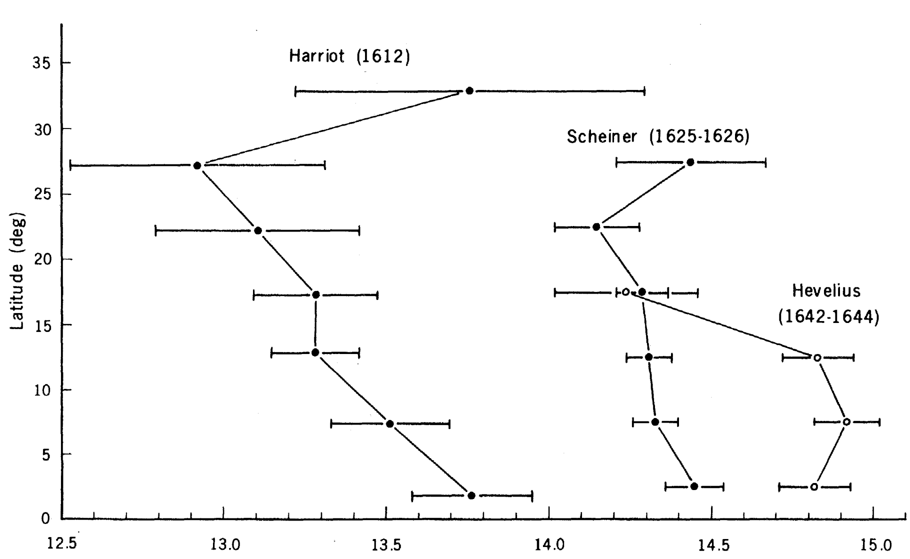

Fig. 1. Sidereal rotation rate of the sun averaged into 5° intervals of latitude (north and south combined). This shows the differential rotation computed from Harriot's observations in 1612 (Table 1) compared with measures (*2*) from 1625 to 1626 (similar to the present) and 1642 to 1644. For each average, the statistical estimate of standard error is represented by an error bar. The sunspots included in the Scheiner and Hevelius results were from the largest sample analyzed (*2*)—that is, the individual spots within 60° longitude of the central solar meridian.

meridian are included, the rate is reduced to 13.04° per day and the standard error is increased to 0.18° per day.

At low altitudes the nonlinearity of atmospheric refraction introduces a slight vertical distortion in the solar image. At a true (geometric) altitude of 1° a spot that is actually at the center of the solar disk would appear 5″ below the midpoint of the apparent vertical diameter, based on an interpolation equation fitted to the refraction tabulated by Allen (*10*). Incidentally, the apparent altitude of the sun's center would be 1°22′ and the vertical diameter would appear compressed by 10 percent, but these large effects would not cause systematic errors in spot positions because of my allowance for linear distortion on the drawings. Although the nonlinear effect is small, the altitude-dependent correction equations, once written to check the significance of refraction, were retained in the reduction program.

Systematic errors originating in Harriot's technique, particularly those that would result in a reduced rotation rate, are a major concern but are very difficult to reconstruct. The perceptual phenomenon of irradiation could cause him to draw the sun too large depending on the image brightness. If, for example, he systematically drew the sun 2 percent too large, the corrected rotation rate would be 13.73° ± 0.10° (standard error of the mean) per day. A test assuming the sun to be 3 percent smaller than drawn failed because this put some spots off the limb. Any systematic errors resulting from telescopic distortions have probably been broken up into random errors because only a part of the sun could be seen in the field, so that scanning was required. Also, various telescopes were used.

Harriot's careful plotting of spot positions is evident from the fact that the average value for the standard deviation of a spot about its computed mean latitude was only 3.2°. It is difficult to escape the conclusion that the sun's rotation, as defined by sunspots, was truly slow at the time Harriot observed it, and that it was accelerating between then and the inception of the Maunder minimum.

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References and Notes

1. J. A. Eddy, *Science* **192**, 1189 (1976); *Sci. Am.* **236** (No. 5), 80 (1977).
2. ———, P. A. Gilman, D. E. Trotter, *Science* **198**, 824 (1977).
3. England was still using the Julian calendar in Harriot's time. The equivalent dates in the Gregorian calendar (for example, to compare with Galileo's observations) are 11 December 1611 through 28 January 1613.
4. Harriot's original sunspot drawings are the possession of Lord Egremont and Leconfield and are retained at Petworth House, Sussex, where they were taken on Harriot's death in 1621. Photocopies of them may by seen at the Bodleian Library at Oxford and the Science Museum in South Kensington, London. In this country, a complete set of Harriot photocopies may be viewed in the History of Science Library of the University of Delaware. I worked from the Delaware copy of HMC 241/8, kindly lent me by J. W. Shirley.
5. J. North, in *Thomas Harriot, Renaissance Scientist*, J. W. Shirley, Ed. (Clarendon, Oxford, 1974), pp. 129–165. The prevailing use of the early Dutch or "Galilean" telescope at the beginning of the 17th century and its field of view are discussed on pp. 144–149 and 158–160. In footnote 55, North suggests that the unnumbered duplicate of the 11 August 1612 drawing could be the original made at the telescope.
6. Baron de Zach remarks on the assertion that Thomas Harriot "had the custom of holding the mathematical brass instruments, when working, in his mouth." A translation of his 1788 paper was reprinted in S. P. Rigaud, *Supplement to Dr. Bradley's Miscellaneous Works with an Account of Harriot's Astronomical Papers* (Oxford, 1833), pp. 57–61.
7. B. Tuckermann, *Planetary, Lunar, and Solar Positions A.D. 2 to A.D. 1649 at Five-day and Ten-day Intervals* (American Philosophical Society, Philadelphia, 1964).
8. R. C. Carrington, *Observations on the Spots on the Sun from November 9, 1853 to March 24, 1861, Made at Redhill* (Williams and Norgate, London, 1863), as cited in J. A. Eddy, P. A. Gilman, D. E. Trotter. *Sol. Phys.* **46**, 3 (1976).
9. A sidereally fixed reference point—the great circle passing through the adopted rotational pole and the ecliptic pole—was used to define "longitude". This is not the heliographic longitude whose reference point rotates with the sun.
10. C. W. Allen, *Astrophysical Quantities* (Athlone, London, ed. 3, 1973), p. 183; refraction tables are on p. 125.
11. F. Ward, *Astrophys. J.* **145**, 416 (1966).
12. H. Wöhl, *Astron. Astrophys.* **62**, 165 (1978).
13. I thank D. J. Mullan for helpful discussions, M. P. Raphael for assistance in selecting spots and for measuring them on the digitizer, and the University of Delaware Computing Center for a grant of computer time. I especially thank J. W. Shirley, who introduced me to the work of Thomas Harriot and whose enthusiastically shared knowledge of Harriot was an invaluable resource.

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Sieve Areas in Fossil Phloem

Abstract. *Phloem tissue of the Pennsylvanian fern* Etapteris *is described from permineralized specimens. Sieve elements possess regularly aligned sieve areas containing pores on the radial walls. The presence of these structures provides a basis for comparison with the phloem of living ferns.*

Vascular plants are characterized by the presence of two principal tissues that make up the conducting system. Xylem is involved in the conduction of water, whereas phloem is responsible for the movement of solutes, principally sugars, in the plant. The basic cell of the phloem tissue is an elongate, thin-walled cell termed the sieve element, which is characterized by the presence of perforations in the walls. These sieve pores are usually aggregated into definite regions on the cell wall that are termed sieve areas. The presence of sieve areas provides the basis for recognition of sieve elements in vascular plants.

The identification of phloem tissue is rare in studies of fossil plants. The features used to determine extant phloem cells are rarely encountered in the fossil record because of the delicate nature and hence the poor preservation of thin-walled phloem cells (*1*, *2*). Consequently, the recognition of fossil phloem is limited to the position these cells occupy in the axis and the identification of sieve areas on the cells. In addition, because of the relatively small size of the cells, their presence in a mineral matrix, and the resolution limits imposed by light microscopy, little information has been obtained to date about the histology of fossil phloem.

This study was performed to describe the structure and occurrence of phloem cells in petiole segments of the Carboniferous fern *Etapteris leclercqii* (*3*) that are preserved in calcium carbonate permineralizations (coal balls). The specimens were collected at the Lewis Creek locality in eastern Kentucky and are stratigraphically associated with the Magoffin marine zone. Although there is some dispute regarding the precise position of these deposits in the Pennsylvanian System, the floral elements clearly suggest that the sediments are of Lower Pennsylvanian age (*4*).

Specimens were prepared for light microscopy by using the cellulose acetate peel technique, and for scanning electron microscopy (SEM) by etching the phloem zone in dilute hydrochloric acid (2 percent of the stock solution) for 10 minutes followed by immersion in saturated EDTA for 8 minutes. After drying, the specimens were mounted on standard SEM stubs with double stick tape, and sputter-coated with approximately 100 Å of gold. The radial walls of the sieve elements were examined at 20 kV in the secondary emission mode.

Figure 1A illustrates a transverse section of the petiole of *E. leclercqii*. The center of the axis is a core of xylem tracheids that in transverse section has the shape of an hourglass (clepsydroid). A zone of phloem tissue, approximately four cells wide, surrounds the xylem. Separating the xylem and phloem is a parenchyma sheath one to two cells wide that is visible in longitudinal section as uniform rectangular cells (Fig. 1, A and C). Crushed parenchyma cells that may

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