SOLAR ROTATION DURING THE MAUNDER MINIMUM

J. A. EDDY, P. A. GILMAN, and D. E. TROTTER
*High Altitude Observatory, National Center for Atmospheric Research,**
Boulder, Colo. 80303, U.S.A.

(Received 8 December, 1975)

Abstract. We have measured solar surface rotation from sunspot drawings made in A.D. 1642–1644 and find probable differences from present-day rates. The 17th century sunspots rotated faster near the equator by 3 or 4%, and the differential rotation between 0 and ±20° latitude was enhanced by about a factor 3. These differences are consistent features in both spots and groups of spots and in both northern and southern hemispheres. We presume that this apparent change in surface rotation was related to the ensuing dearth of solar activity (the Maunder Minimum) which persisted until about 1715.

1. Introduction

Modern theory attributes the production and periodicity of sunspots to the action of a hydromagnetic dynamo, whose hydrodynamic component is supplied in part by differential rotation in surface layers of the Sun. In consequence we might expect that aspects of solar rotation would change, systematically, with the solar cycle. Searches for this effect in solar differential rotation have not been conclusive, and probably indicate that evidence, if present, is slight. It may be barely within the capability of present Doppler-velocity data, or hidden in statistical fluctuations or in the ambiguous definition of 'quiet' and 'active' periods.

This suggests that a clearer demonstration might be found at times in the long-term behavior of the Sun when activity was at a prolonged, anomalous state. A recent study reveals that the period A.D. 1645–1715 (the Maunder Minimum) was such a time, and that during this span of seventy years solar activity dropped to near-zero levels (Eddy, 1976). Contemporary sunspot reports, eclipse observations, and the historical records of aurorae and of atmospheric carbon-14 seem to confirm the anomaly and leave open the question of whether the 11-year cycle operated at all during the time (Figure 1). In any case, if the Maunder Minimum were real, we should expect that the action of the dynamo was at the time reduced, with anomalous rotation a possible cause. We were thus led to examine solar observations of that era for evidence of whether the surface of the Sun rotated in manner different from today.

2. Observational Data

The only information on surface rotation during our period of interest comes from contemporary drawings of the Sun and sunspots. Other 'tracer' data are not available, since prominences were not discovered until 1706, at eclipse, and not

---

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Solar Physics **46** (1976), 3–14. *All Rights Reserved*

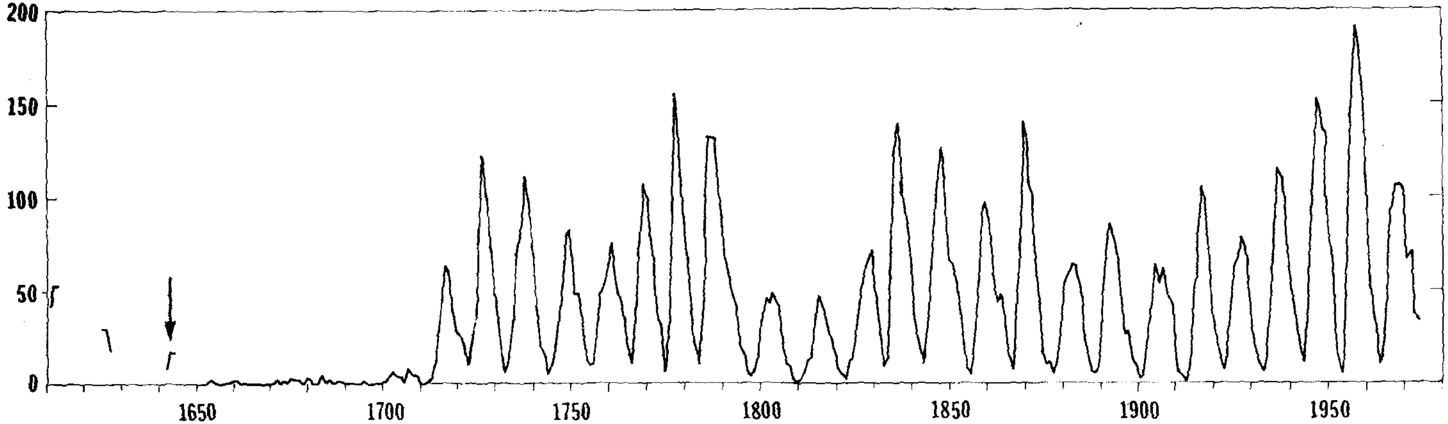


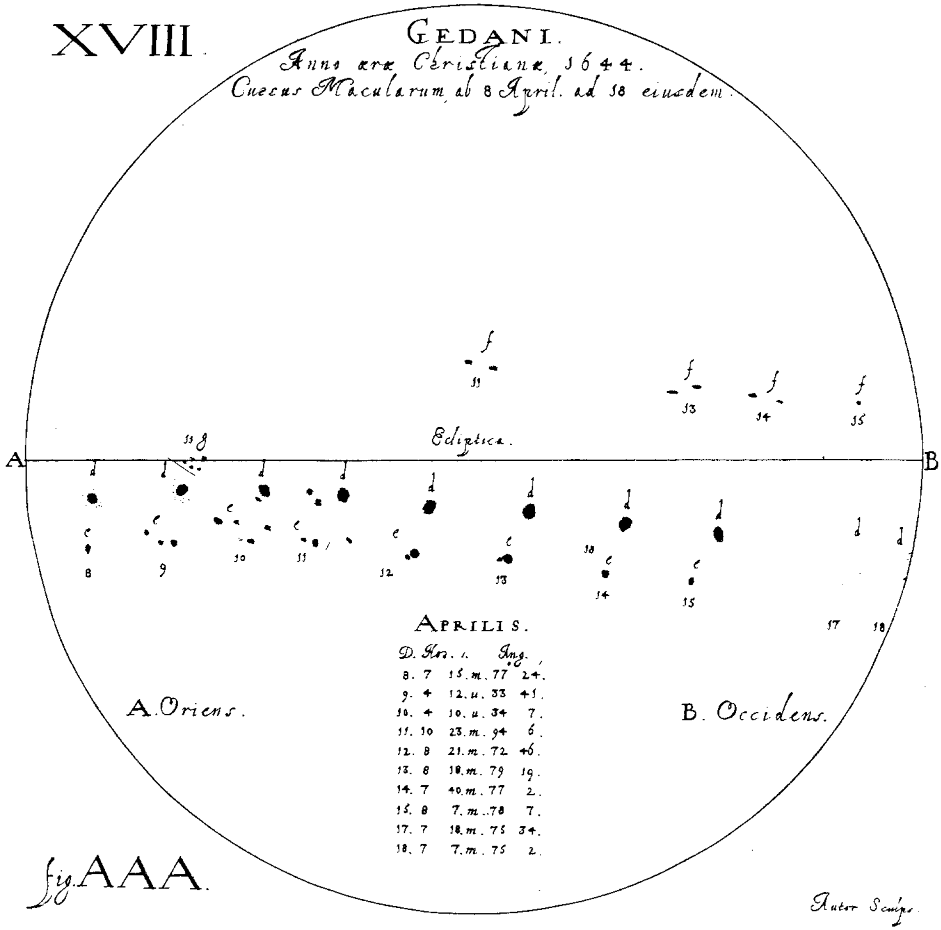
Fig. 1. Annual mean sunspot numbers, A.D. 1610–1974, from Waldmeier (1961) and Eddy (1976). Arrow marks the period of this study, 1642–1644.

studied systematically for another 150 years; useful spectra and monochromatic images came, of course, much later. Sunspots were observed and recorded in the 17th century much as they are today: with telescopes of a few meters focal length and projection of the solar image upon a card, from which a full-disk drawing was made (Scheiner, 1630; King, 1955). These pictures are surprisingly good, and reveal most of the detail shown in sunspot drawings of today.

Modern use of photographs to trace solar rotation is complicated by proper motions of sunspots, uncertainty in the definition of reference points and solar longitudes near the limb, and inevitable statistical scatter. In using 17th century records other problems are added: we deal perforce with drawings – of uncertain pedigree and unspecified coordinate reference – and what is worse, we seek to measure sunspots when there were almost none to see. During the 70 years of the Maunder Minimum there were fewer sunspots recorded than are seen in a single year of normal activity today, and there were 32 years with estimated annual mean sunspot numbers of zero (Eddy, 1976). The most promising periods for our purpose are near the beginning and end of the Maunder Minimum, when solar behavior had changed sufficiently to define a long-term anomaly but with enough spots present to give a meaningful sample.

The Maunder Minimum has been given an arbitrary beginning date of 1645; in fact sunspots seem to have disappeared gradually after their telescopic discovery in 1610, so that somewhere between 1630 and 1650 the prolonged minimum had set in (Figure 1). We are fortunate to have a fairly continuous record of full-disk drawings of the Sun for a period from the autumn of 1642 through autumn 1644, which samples the onset of the long quiet of the Maunder Minimum. The drawings are of fine quality and were made by an astronomer of good credentials and printed in his private observatory printshop, thus reducing the possibility of errors of redrafting and artistic license. The observer was Johannes Hevelius (1611–1687) in Danzig; the solar drawings were included as an incongruous appendix in his large and beautiful book on the Moon, *Selenographia* (1647).

Hevelius' method was to present several days drawings on a single Sun disk (Figure 2). This realized an obvious economy in reproduction but his main reason was probably his own interest in the tracks of sunspots and, like us, the solar rotation. His method of presentation enhances our accuracy of measurement, since spots appear as tracks across a single reference circle. Hevelius was careful to label each spot and to specify the date and time (to nearest minute) of each day's drawing, bequeathing an observational record as good as one could make today, fundamentally limited only by the imperfect clocks of the day. This presentation of multiple days on a single drawing is practical only at times of low activity. For most of the period of the Hevelius data there were but one or two groups on the Sun at a time; reconstructed annual mean sunspot numbers for the three years were 6, 16, and 15 (Eddy, 1976). We cannot tell where these three years fell in a presumed 11-year cycle, although they are generally taken as near minimum (Waldmeier, 1961).



D.	Hor. ′	Ang. ° ′
8.	7 15. m.	77 24.
9.	4 12. u.	33 45.
10.	4 10. u.	34 7.
11.	10 23. m.	94 6.
12.	8 21. m.	72 46.
13.	8 18. m.	79 19.
14.	7 40. m.	77 2.
15.	8 7. m.	78 7.
17.	7 18. m.	75 34.
18.	7 7. m.	75 2.

Fig. 2. One of the 26 engravings of the solar disk from the appendix to Hevelius' *Selenographia* (1647). On this plate 10 days' observations of sunspots in April 1644 are shown on a single rectified disk. White-light faculae (far right) are also shown.

There are 26 solar plates in the *Selenographia*, covering 224 days observations in a 24-month period. From these we measured the heliographic coordinates of all individual sunspots, using transparent overlays of appropriate Stonyhurst Sun Disk grids (Cortie, 1908). Daily spot positions were determined to an estimated accuracy of ±0.5°. All spots recorded by Hevelius during the time were within 20° of the solar equator – a low latitude clumping which we would expect if the 11-year cycle were approaching a minimum. In fact throughout the Maunder Minimum spots were confined to low latitudes with no reported appearances of new-cycle, high-latitude spots above about 10° (Maunder, 1922).

3. Results

Using these spot positions and the times of observation given by Hevelius we calculated daily synodic solar rotation rates, R, and a mean rate $\bar{R}$ for each of the

TABLE I
Solar rotation, A.D. 1642–1644
(Synodic rotation rate (degrees per day) $\bar{R}$, and standard deviations, σ and $\sigma/\sqrt{N}$ from sample N of sunspot measurements from Hevelius' *Selenographia.*)

			Latitude (°)								
			north				south				
Longitude from C.M.	tracer		20–15	15–10	10–5	5–0	0–5	5–10	10–15	15–20	Total sample
≤40°		$\bar{R}$	13.35	13.89	13.78	13.97	13.74	13.89	13.72	13.22	
		σ	1.03	0.85	1.17	0.96	0.71	1.02	1.11	1.53	
		$\sigma/\sqrt{N}$	0.29	0.17	0.13	0.19	0.14	0.12	0.17	0.38	
		N	13	26	83	25	26	67	42	16	298
≤40°	groups	$\bar{R}$	13.32	14.06	13.72	13.89	13.76	13.81	13.71	13.11	
		N	2	3	22	5	3	14	9	1	59
≤60°	spots	$\bar{R}$	13.28	14.03	13.91	14.03	13.63	13.95	13.71	13.22	
		σ	0.96	0.88	1.35	1.04	0.78	1.36	1.06	1.53	
		$\sigma/\sqrt{N}$	0.24	0.15	0.14	0.18	0.13	0.15	0.15	0.38	
		N	16	34	100	35	34	81	48	16	364
≤60°	groups	$\bar{R}$	13.37	14.08	13.66	13.70	13.66	13.88	13.69	13.24	
		N	2	6	25	5	5	12	10	1	66

			north and south			
			20–15	15–10	10–5	5–0
≤40°	spots	$\bar{R}$	13.28	13.78	13.83	13.85
		σ	1.31	1.01	1.10	0.84
		$\sigma/\sqrt{N}$	0.24	0.19	0.09	0.12
		N	29	68	150	51
≤40°	groups	$\bar{R}$	13.25	13.79	13.76	13.84
		N	3	12	36	8
≤60°	spots	$\bar{R}$	13.25	13.84	13.93	13.83
		σ	1.26	1.00	1.35	0.93
		$\sigma/\sqrt{N}$	0.22	0.11	0.10	0.11
		N	32	82	181	69
≤60°	groups	$\bar{R}$	13.32	13.84	13.73	13.68
		N	3	16	37	10
Modern era (Ward, 1966)		$\bar{R}$	13.30	13.40	13.48	13.53

eight 5° latitude belts between ±20°. Data were restricted to spots within 60° of the central meridian, and an even more restrictive set within 40°. We also calculated mean rotation rates for identifiable spot groups. The mean rates, standard deviations, and number of data points in each sample are compiled in Table I. We also give the same data for combined northern and southern

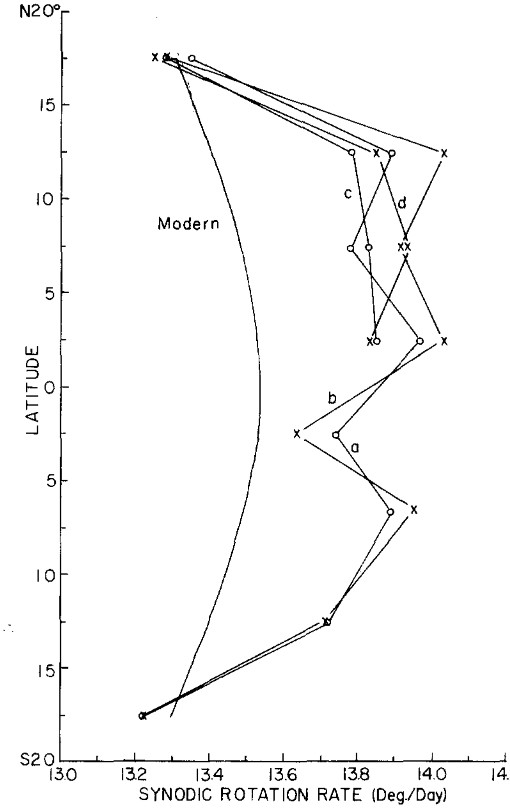


Fig. 3. Daily solar rotation rate $\bar{R}$, A.D. 1642–1644: (a) spots within 40° of central meridian; (b) within 60°; (c) combined northern and southern hemispheres, within 40° of central meridian; (d) same, within 60°. Comparison curve is for all spots in period 1905–1954 (Ward, 1966).

hemispheres, and, for comparison, the nominal rotation rates determined by Ward (1966) for all spots in the period from 1905–1954.

Two features are evident in the rotation profiles (Figure 3). First, near the equator the 17th century spots rotate faster than their modern counterparts, by as much as 0.5°/day in some cases, or between 3 and 4%. Secondly, the total differential rotation profile is substantially sharper in the Hevelius sample: rotation falls much more steeply with latitude than is true today. The differential rotation between the equator and ±20° latitude appears to be intensified by about a factor 3. Most of the variation in rotation occurs between the 10–15° and the 15–20° latitude belts. The rotation rate at ±20° is about equal to the modern value, and above that latitude we have no information.

How significant are these findings? Figure 4 compares the 17th Century averaged rotation rates with modern values, with bars showing estimates of the standard deviation $\sigma/\sqrt{N}$ for the mean rotation rate for each latitude belt from Table I. We see that the three latitude belts closest to the equator rotate faster

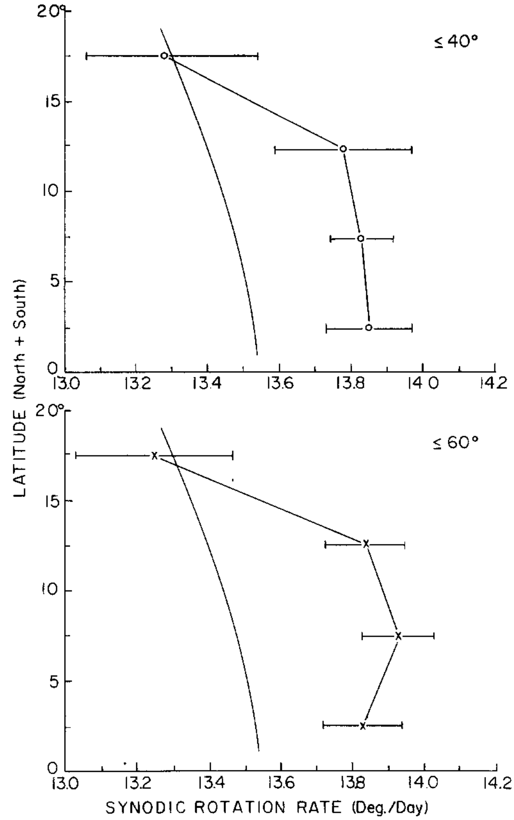


Fig. 4. 17th century combined N+S hemisphere rotation rate for zones within 40° and 60° of central meridian, showing estimated standard deviation of mean rotation rate determined for each latitude belt. Comparison curves are for all spots, 1905–1954 (Ward, 1966).

than modern rates by between 2 and 3 standard deviations. Thus, the faster rotation rate seems quite real. Furthermore, the sharp drop in rotation rate between these and the 15–20° belt also appears real, though at a lower level of significance.

In addition, even without combining hemispheres, departures from the modern norm are all on the side of faster rotation. And finally, although northern and southern hemisphere data are quite independent, there is a convincing symmetry in the rotation curves derived for the two sets of data.

The fluctuations for rotation of spot *groups* are generally much smaller than for individual spots, indicating that a significant part of the scatter in the latter set is due to differential motions within groups. Figure 5, which compares group and spot rates, shows that the fast equatorial rate and steep fall-off with latitude are equally present in the group rotation data.

As another check (not shown) we separated the data into two consecutive one-year periods (October 1642–October 1643, and November 1643–October 1644) and found the same basic profile with latitude for each set.

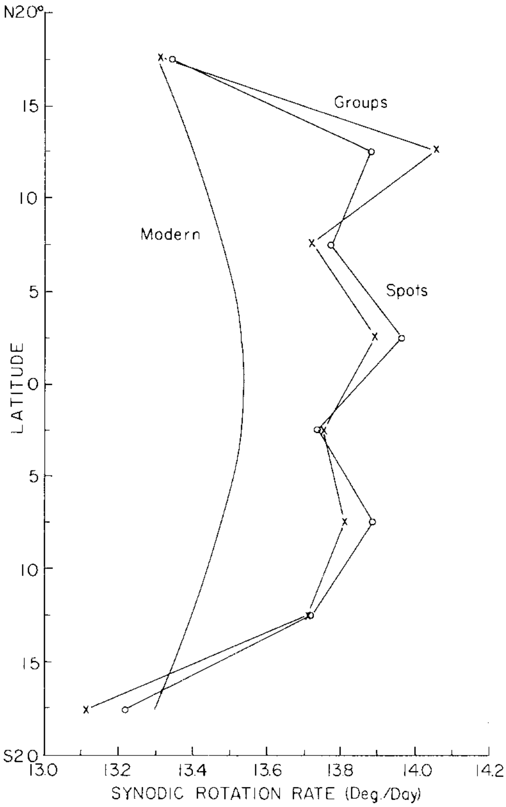


Fig. 5. Daily solar rotation rate $\bar{R}$, A.D. 1642–1644, for spots within 40° of central meridian (also shown in Figure 3a) and for groups within 40°. Comparison curve is for all spots, 1905-1954 (Ward, 1966).

It is of historical interest that evidence for the differential rotation is present in the 1642–1644 data, for it means that Hevelius himself could have established its existence more than two centuries before it was finally demonstrated by Carrington (1863).

One can invent systematic errors which would artificially shift the solar rotation curve toward apparent faster velocity. One is a consistent error in drawing the circle of the Sun. Had Hevelius or his engraver made the disk circle persistently too small while keeping the spots on the original scale, it would lead to exaggerated rotation rates. But the exaggeration would increase with distance from the equator and this does not appear to be the case. Another possibility is a persistent clock error, but this would have to be maintained over the more than 2-year span of the data sample and would constitute an error wholly intolerable to an astronomer of Hevelius' ability.

4. Conclusions

Consideration of all factors leads us to believe that the differences are real, and that at the onset of the Maunder Minimum the low latitude photospheric layers were rotating more rapidly than at present and with enhanced differential slippage. This effect may have been related to the accompanying decrease in sunspot production, as cause or result. A speeding up of 3 or 4% at the equator is significantly more than the fluctuations in velocity now found in normal cycle operation, where differences in rotation rate from one cycle to the next are only a few hundredths of a degree per day (Ward, 1966), even though cycle intensity (sunspot number) varies by a factor of two or more.

The anomalous rotation in 1642–1644 may represent velocities near the limit of a critical range for the effective production of sunspots by the dynamo, which could have brought on the prolonged sunspot dearth that followed. Another possibility is that decreasing dynamo action during the Maunder Minimum resulted from an unobservable subsurface process, and that the accelerated surface rotation found here was a secondary phenomenon, resulting from reduced braking by the depleted electromagnetic torques associated with spot and active region fields.

Recent dynamo theories for solar magnetic field (reviewed in Stix, 1976) rely heavily on stretching of field lines by the subsurface radial gradient of angular velocity in the convection zone. In order to reproduce the equatorward migration of the zones of spot formation as the solar cycle progresses, they generally require that the angular velocity increase inwards. If the high surface equatorial angular velocity we have found arose through a redistribution of angular momentum from deeper in the convection zone, then the angular velocity at those depths should have been less than for current solar cycles. Thus, the radial gradient of angular velocity, and therefore the strength of its dynamo action, would have been reduced. If the gradient were reduced enough for a long enough time, then the toroidal fields might have been too weak to produce sunspots with the usual frequency, possibly for as long a period as the Maunder Minimum.

We are now investigating other contemporary sunspot drawings to establish the character of solar rotation earlier in the 17th century.

Acknowledgements

We are indebted to the Naval Observatory Library and to Dr Owen Gingerich for our acquaintance with the *Selenographia*, to Dr Stephanie Benton for help in translation, and to Dr Oran R. White for helpful comments. The work of J.A.E. was funded wholly by NASA Contract NAS5-3950.

Appendix: A Test of Hevelius and R. C. Carrington

Any sequence of projected images of the Sun will require correction for the apparent rocking back and forth of the solar axis of rotation with respect to the celestial pole. In modern practice this correction is tabulated in the *American Ephemeris and Nautical Almanac* as the "*P*" angle, which arises from the combination of two projection effects: the 23.43° obliquity of the ecliptic and the 7.25° inclination of the solar equator to the ecliptic. These periodic functions $P_0(t)$ and $P_i(t)$ are out of phase and combine to produce the tabulated angle $P(t)$ with present extremes of ±26.34°.

The orientations of the solar images in the *Selenographia* are unspecified but it is apparent from the sunspot tracks that the disk drawings were *not* fully corrected to put the solar equator parallel to the celestial equator (the "Ecliptica" or "Oriens"/"Occidens" line on each plate.) In preparing the drawings for printing Hevelius included part but not all of the modern "*P*" correction.

In the course of our reduction we measured the image rotation required on each plate to bring the apparent equator of the Sun into coincidence with the east-west fiducia, by aligning sunspot tracks to latitude lines on the Stonyhurst disks. Our empirical correction is shown in Figure 6 as a function of day of year: it fits a sinusoid of amplitude 7 or 8°, with ascending node in late August/early September. This residual in Hevelius' data thus describes rather well the projection on the sky of the Sun's axis of rotation – which is the function $P_i(t)$. The solar equator was known to be inclined to the ecliptic in Hevelius' day but the precise value (and possible precession) were not well established: Galileo had estimated it to be "a small angle" and Scheiner, in 1630, had given it limits of 6 to 8° (Grant, 1852). The modern value for the solar inclination and the elements which describe its slow precession were not well determined until the middle 19th century, when Carrington (1863) determined the parameters now used from 8 years of his own sunspot drawings, 1853–1861.

The presence of an accurate representation of $P_i(t)$ in the Hevelius data reveals several things:

(1) Hevelius had made accurate correction in orienting each drawing for the obliquity of the ecliptic, $P_0(t)$. Significant for us is not that he did this (for the obliquity and even its long-term changes were then established) but that he did it so carefully that we can salvage the now-known residual function $P_i(t)$. This lends credence to the other information in the solar drawings, which we presume were executed with equal care.

(2) In the appendix to the *Selenographia* were all information needed to determine the inclination of the Sun's axis of rotation (i and Ω, the longitude of ascending node) had Hevelius or subsequent readers chosen to do it.

(3) Figure 6 allows us to determine contemporary elements (i and Ω) for the 1642–1644 epoch, and, in principle, to check the Carrington *precession* elements over a baseline of more than 200 years.

In Figure 6 we have plotted the function $P_i(t)$ for the Carrington elements ($i = 7°15'$, $\Omega = 73°40'$) for 1850. The Carrington precession ($+50.25'' t$, where t is time in years from 1850) would shift the 1643 node to right ascension 70°47′ – a change of a little less than 1%, or a shift to the left of 2.9 days, as shown. Our empirical corrections to the Hevelius plates are not adequate to distinguish between the shifted and unshifted curves, and thus we cannot distinguish between

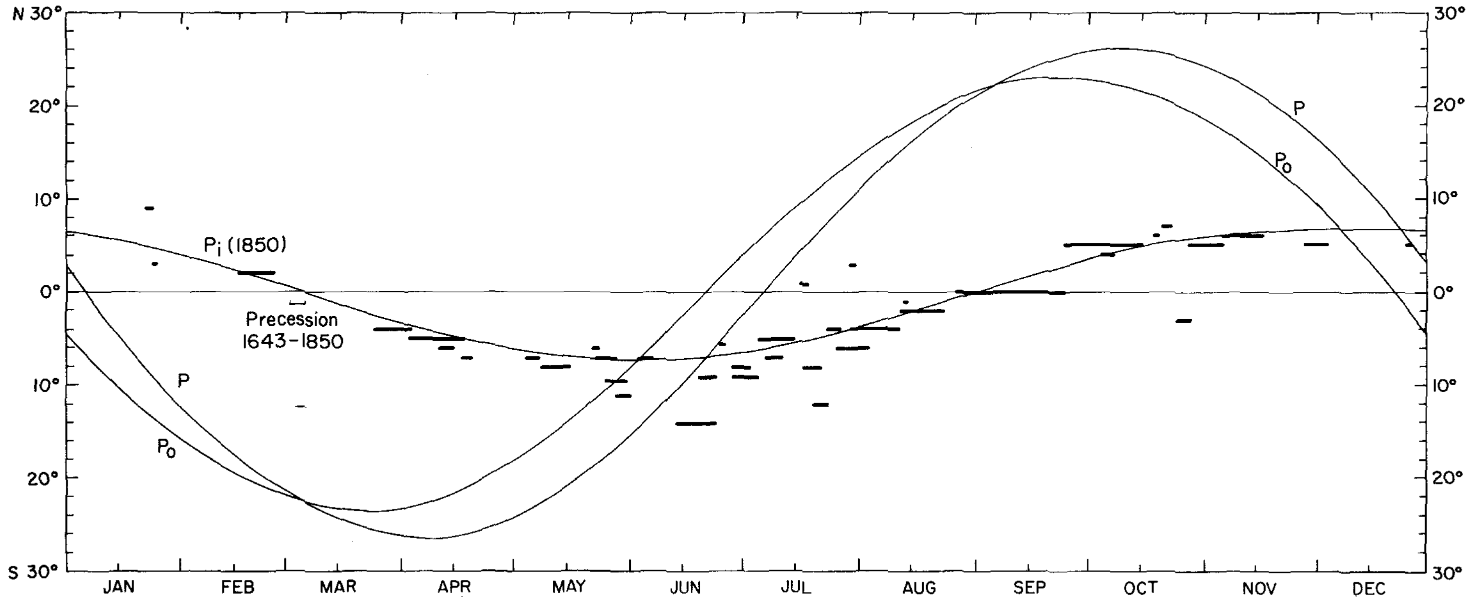


Fig. 6. Empirical corrections to solar plate orientations in *Selenographia* from this study (bars), compared post facto with curve P_i of projection of inclination of solar rotation axis for A.D. 1850 showing precessional shift to A.D. 1643, based on elements of Carrington (1863). Empirical corrections falling substantially off the smooth curve P_i were corrected to it when computing rotation. P_0 is the projection of the obliquity of the ecliptic. P, the sum of P_i and P_0, is the total projection function tabulated in the *American Ephemeris and Nautical Almanac*.

Carrington's precession and none. At best we can place an upper limit on precession of about ±4 times the 50.25″ rate for the 1643–1850 period. Carrington's method (which was recently reapplied by Schröter and Wöhl, 1975) was based on apparent coordinates of individual spots and is more precise than our rough check, even though he applied it to a much shorter baseline. If nothing else, our work on the Hevelius data would seem to confirm Carrington's assessment (1863, p. 245) of the accuracy of his elements for the solar axis:

> "I believe I shall not be far wrong in saying that a sensible improvement on the above values will not be obtainable by an expenditure of less than five thousand pounds".

References

Carrington, R. C.: 1863, *Observations on the Spots on the Sun from November 9, 1853 to March 24, 1861 Made at Redhill*, Williams and Norgate, London.
Cortie, A. L.: 1908, *J. Brit. Astron. Assoc.* **18**, 26.
Eddy, J. A.: 1976, *Science* (in press).
Grant, R.: 1852, *History of Physical Astronomy* (reprinted by Johnson Reprint Corp., N.Y. 1966), pp. 216–7.
Hevelius, J.: 1647, *Selenographia Sive Lunae Descriptio*, Danzig. (Reprinted by Johnson Reprint Corp., N.Y., 1968).
King, H. C.: 1955, *The History of the Telescope*, Sky Publ. Co., Cambridge.
Maunder, E. W.: 1922, *Monthly Notices Roy. Astron. Soc.* **82**, 534.
Scheiner, C.: 1630, *Rosa Ursina sive Sol ex Admirando Facularum...*, Bracciano.
Schröter, E. H. and H. Wöhl: 1975, *Solar Phys.* **42**, 3.
Stix, M.: 1976, in J. Kleczek (ed.), *Basic Mechanisms of Solar Activity*, IAU Symposium 71, in press.
Ward, F.: 1966, *Astrophys. J.* **145**, 416.
Waldmeier, M.: 1961, *The Sunspot Activity in the Years 1610–1960*, Schulthess & Co., Zürich.