ROTATION RATE OF HIGH-LATITUDE SUNSPOTS

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Abstract. Rotation rate of 19 high latitude (28–44°) short-lived sunspots collected in 1978–1979 are compared with Newton and Nunn's (1951) recurrent spots rate. To reduce the effect of proper motion in spots of new regions, our measurements start only when the spots have matured or very nearly so. Compared with the expression $\omega = 14.38 - 2.96 \sin^2 \phi$ derived from 1934–44 data by Newton and Nunn, our results show a slightly lower differential rotation in the 28–40° zone. They are in better agreement with the Greenwich average results of the five solar cycles beginning 1878: $\omega = 14.37 - 2.60 \sin^2 \phi$.

1. Introduction

The solar rotation rate for spots derived from recurrent sunspots in the solar cycle 1934–44 by Newton and Nunn (1951) has long been a classic. The sidereal rotation rate for recurrent spots was found to be $14.38 - 2.96 \sin^2 \phi$, where ϕ is the latitude. They showed that this result is in satisfactory accordance with values from similar data for the five previous cycles beginning 1878, a century ago. The same result was also shown recently by Kearns (1979) to be in agreement with his analysis of the 1978 data. While Newton and Nunn's analysis was plausible in many aspects and the extent of the data vast, it is lacking in one area, namely, the number of data points used in the high latitude zone.

Of the 136 recurrent spots used in the Newton and Nunn analysis, only two were in the above 30° latitude in the solar cycle 1934–44. In the first four of the five previous cycles, there were no recurrent spots above 30°. The fifth cycle also had only two recurrent spots in the 30–35° latitude zone. And so these very few spots played a very large role in shaping the tail-end of the much-quoted Newton and Nunn rotation curve, actually for recurrent spots, but popularly known simply as the Sun's rotation rate.

The difficulty, of course, lies beyond the investigator's control. The Sun simply does not produce many recurrent spots in its high latitudes.

The appearance of high latitude spots ushers in a new solar cycle but the high latitude is not a fertile land for spots. Only a very small fraction of spots manage to survive there. And the very high latitudes (the 40's) are reserved for none but the solar maximum year of the largest solar cycles. Kopecký (1958, 1959) compiled a list of all observed spot groups and spots with latitudes ≥40° from 1874 to 1957. There were 66 entries on the list, including those observed only once. The single most productive year of these very high latitudes spots was 1957 with 19 spots.

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A total of 29 spots ranging from 40–48° were observed from 1955 to 1957, the maximum years of the largest solar cycle on record. The rotation rate of a sunspot at N 48.3° observed for an incredible 15 days in 1956 was reported by Waldmeier (1957) to be $12.35° \pm 0.15°\ d^{-1}$, within 3% (slower) of the Newton and Nunn rate.

In his 1959 paper Kopecký had rotation rates of 7 single spots from the list of 66 with 40° latitude and above that had a time lapse of 5 days or longer between observations. The data will be compared with ours in Section 4.

Since another solar maximum is upon us, we decided to collect and measure the shorter-lived spots in the high latitudes and to compare their rotation rates with those of the recurrent spots of the lower latitudes and to supplement Kopecký's very high latitude data.

2. Data

Since Big Bear Solar Observatory has been in full operation for less than a solar cycle, our study is confined to the current cycle which began in the latter part of 1975. Full-disk filtergrams from the 22 cm vacuum refractor telescope with a 0.7 Å FWFM band Fabry–Perot filter are used. The telescope optics are carried by invar rods which keep the optics rigidly located relative to one another and the magnification fixed. The Sun's disk is photographed on the film for 10 hr at the rate of three per minute on a normal day. For our measurements, the 35 mm filtergram is projected in a Theodolite viewer onto a screen forming an image 18 cm in diameter. X and Y coordinates of the center of mass of the spot are read off from cross hairs and converted to heliographic longitude and latitude. Two independent measurements are made for each spot. Days when spots are within 20° from the limbs are not used. Rotation rates are obtained from the difference in longitudes on the first and last day of measurements and the time lapse.

Data used in our study include those that satisfy all of the following conditions:

(1) Only spots with latitudes higher than 28° are included.

(2) To greatly reduce, if not eliminate, the effect of proper motion commonly occurring in new bipolar spots during its growth stage, our first day measurement of a spot takes place only when the spot has matured or very nearly so. The area of a spot is usually a good indication of its developent stage.

(3) Although we do not take daily measurements of the spots used in this analysis, we make sure that no substantial morphological change takes place in the intervening days between the first and last measurement.

(4) The first and last measurement of the same spot is at least 4 days apart.

This way we collected 19 spots (all in 1978 and 1979) out of a total of 168 spots counted from the *Solar Geophysical Data* from 1975 through May of 1979 that lived at least 2 days at latitudes 28° and higher. Table I lists the spots used in this study. The 'Remarks' column indicates the visual judgement of the development stage of the region the spot is in as well as the polarity of the spot.

TABLE I
The sunspots used in this study

No.	Latitute	Dates	Siedereal rotation rate (d^{-1})	Remarks
1.	+29.8	Feb. 14–24, 1978	13.59 ± 0.04	βP, large spot, newish region
2.	−31.1	Mar. 13–19, 1978	13.51 ± 0.06	βP, newish region
3.	−34.5	Mar. 13–19, 1978	13.47 ± 0.08	βF, newish region
4.	−44.0	Apr. 12–23, 1978	12.91 ± 0.04	αP, medium stable spot
5.	−29.5	May 10–26, 1978	13.74 ± 0.06	αP, small spot, oldish region
6.	+44.0	Aug. 15–19, 1978	14.14 ± 0.07	βP–αP, new region
7.	+31.5	Sep. 7–15, 1978	13.97 ± 0.07	βP, developed region with new flux emerging in between
8.	+33.7	Sep. 8–13, 1978	13.77 ± 0.04	βF, developed region with new flux emerging in between
9.	+38.0	Sep. 12–22, 1978	13.32 ± 0.06	βB–αP, medium stable spot
10.	+28.8	Sep. 13–23, 1978	13.85 ± 0.04	βP, large spot, young region
11.	+28.1	Oct. 21–27, 1978	13.88 ± 0.07	βP, new region
12.	+31.8	Oct. 21–27, 1978	13.87 ± 0.03	αP, small spot
13.	−28.1	Nov. 17–26, 1978	13.62 ± 0.04	αP, stable spot, youngish region
14.	−38.1	Feb. 10–18, 1979	13.76 ± 0.03	βP–αP, new spot, P drifted poleward
15.	+36.0	Feb. 23–Mar. 1, 1979	13.20 ± 0.06	Elongated P spot
16.	+28.5	May 9–18, 1979	13.92 ± 0.04	αP, stable spot
17.	−31.3	May 14–18, 1979	13.73 ± 0.03	βF, new region
18.	−29.1	May 14–20, 1979	13.67 ± 0.07	βP, new region
19.	−34.0	May 22–29, 1979	13.36 ± 0.03	αP, stable small spot

3. Results

The results are superposed on Newton and Nunn's curve as crosses in Figure 1. The average uncertainty introduced into the rotation rate due to random error in measurements is ±0.05° d^{-1}. The circled crosses indicate the average results when binned in 28–30°, 30–35°, and 35–40° zones of latitude. Because of the scatter, an average is not given for the 40°–45° zone.

The following points are noted from our data:

(1) The scatter in our data is larger than that of Newton and Nunn, as one might suspect when dealing with the rotation rate of spots spanning an average of 7.4 days instead of 27 days.

(2) The scatter is not centered along the Newton and Nunn curve. It is shifted toward a higher rotation rate (less differential rotation).

(3) The averaged result agrees well with Newton and Nunn's curve at 28.8° latitude. It is 1.2% higher in the 30–35° zone and 1% higher in the 35–40° zone (in which we have only three data points). Up to 40° (the next zone 40–45° will be discussed separately) the averaged results show a definite differential rotation but at a slightly flatter rate than Newton's and Nunn's. In the expression $\omega = A - B^2 \sin \phi$, B is found to be 2.96 for the solar cycle 1934–44 by Newton and Nunn, in contrast to the average B value of 2.60 from the previous five cycles. The broken line in Figure 1

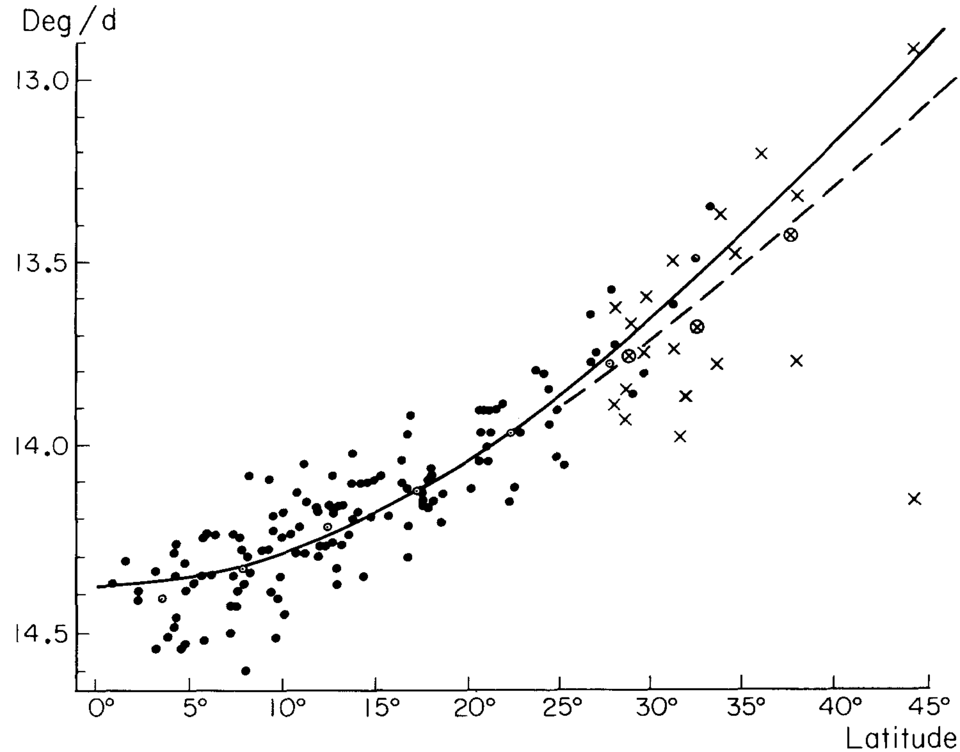

Fig. 1. Dots, circled dots and solid line up to 35° latitude are original Newton and Nunn's results from recurrent sunspots, 1934–44. The curve beyond 35° latitude is contracted from the same expression $\omega = 14.38 - 2.96 \sin^2 \phi$. *Ordinate*: daily sidereal motion, deg d^{-1}. *Abscissa*: heliographic latitude. The broken line is constructed from the expression $\omega = 14.37 - 2.60 \sin^2 \phi$, the average result of the 5 cycles beginning 1878. Crosses are data from our 1978–79 study. Circled crosses are binned results in 28–30°, 30–35°, and 35–40° latitude zones.

is constructed with the latter *B* value. Our short-lived spots of 1978–79 are closer to these values.

(4) For non-recurrent spots that lived 9–10 days, Newton and Nunn found them to rotate more differentially then the recurrent spots with a *B* value of 3.36. Our data show the opposite tendency.

(5) In the 40–45° latitude zone we have only two spots. One at S 44° lived 12 days and had a rotation rate of 12.91° d^{-1} comparable to the 12.95° d^{-1} rate calculated from Newton and Nunn's expression. The other spot at N 44° had a highly unusual rotation rate. The region was born on August 12, 1978. Bipolar spots emerged the next day. By the 15th, *P* spot was at its maximum and we took our first measurement. Four days later it diminished to a tiny spot and we ended our measurement on the 19th. The four days have an average rotation of 14.14° d^{-1}. This is 9% higher than the rate calculated from Newton and Nunn's expression.

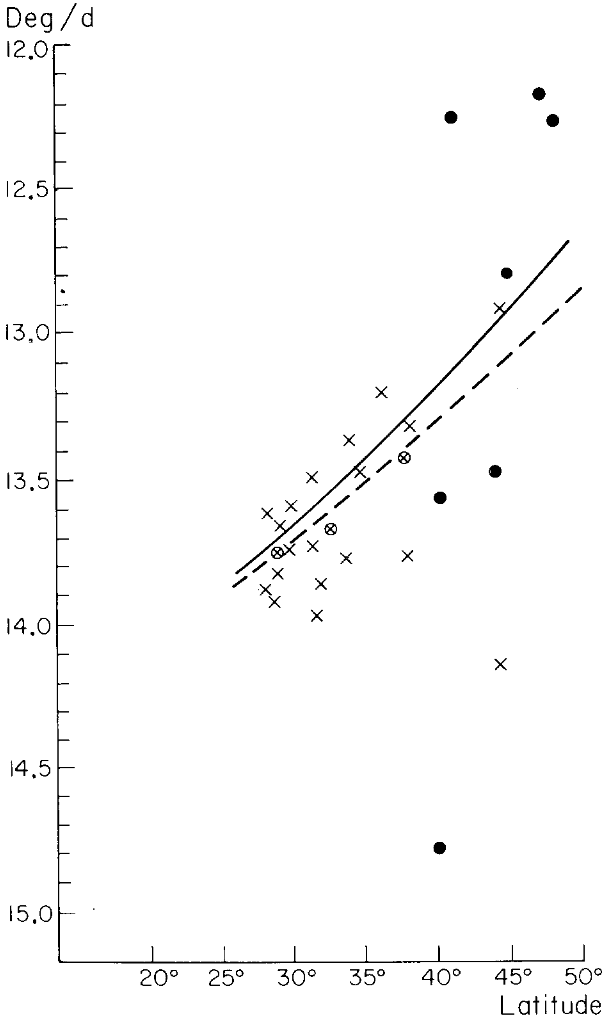

Fig. 2. 1978–79 spots are shown as crosses. Dots are 1956–57 spots from Kopecký. Solid line corresponds to $\omega = 14.38–2.96 \sin^2 \phi$. Broken line corresponds to $\omega = 14.37–2.60 \sin^2 \phi$.

4. Discussion

The seven data points from Kopecký's latitudes 40° and above spots mentioned earlier in Section 1 are plotted as dots along our data (the crosses) in Figure 2. As pointed out in his paper, the recurrent rates of Newton and Nunn (solid line) and the Greenwich average (broken line) are reasonable approximations of these spots. The rotation rates of these spots also show a greater scatter than our 1978–79 data. We do not know if the greater scatter at increasing latitudes is real. There are differences in the treatment of data between the two sets. Kopecký's data, for instance, made no restriction on the maturity of the spot such as condition (2) imposed on our data in

Section 2. One does not know the true effect of this restriction on the rotation rates until one knows the life story of high latitudes sunspots. Waldmeier (1957) analyzed the daily rotation rate of the spot at N 48.3° for 15 days and found the second half of the disk passage had a near constant rate that was 0.57° d^{-1} faster than the near constant rate of the first half of the disk passage. If all high latitude spots were to behave in this manner, one would still have difficulty explaining the scatter which is greater by a factor of 2.

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