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THE ROTATION OF THE SUN FROM MOUNT WILSON SUNSPOT MEASUREMENTS

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1. Introduction

We have recently completed the measurement and reduction of 62 years of white-light solar images taken at the Mount Wilson Observatory. So far the data have been analyzed for differential rotation and time variations of this quantity, among other parameters. The data, the measurement and reduction techniques, and the results obtained so far are described in two publications: (Howard, Gilman, and Gilman, 1984; Gilman and Howard, 1984). This is a brief review of that work.

The interval covered by these data is 1921-1982. The measurements were carried out in an interval of two years by Pamela Gilman. The homogeneity in the reduction and in the observations themselves are two advantages of these measured spot positions over other data. A further advantage of this analysis —— and a characteristic that distinguishes it from nearly all previous work —— is that measurements were made of individual sunspots, not just sunspot groups.

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2. Data

The white-light solar images have been obtained with the same focal-plane shutter mechanism at the 60-foot tower telescope at Mount Wilson throughout the interval. The 18.3 m focal length lens now in use was originally installed about 1916. The coelostat mirrors were replaced twice during the interval.

The image diameter is 170 mm. Pole markers on the images designate the axis of the solar rotation. The focal-plane shutter gives an exposure time of about 1/1000 second for the f/60 beam. The observing log contains the time and data of each observations, the focus setting, temperature and other information.

3. The Measurements

An electronic measuring pad placed over a light box was used for position measures on the plates in two dimensions. The accuracy of such measurements is about 0.1 mm, which is about one arc sec on the plates.

Each plate was positioned on the tablet with the rotation axis of the sun aligned with one axis of the tablet. The limb was defined by 8 equally spaced measurements. Then each spot umbra (penumbrae were not mesured) was measured with two position measures of the cross-hair. This enabled us to calculate the position and approximate area of each spot.

Altogether nearly 15,000 usable images were obtained in the 62-year interval. Nearly 335,000 daily sunspots were measured on these plates.

Only sunspot umbrae were measured in this program because we felt that they represented the fundamental positions and areas of the spots.

4. The Analysis

Rotation rates of individual sunspots were determined only from one-day differences of longitude mesurements. In order to identify individual sunspots from one day to the next using a computer program, which is a difficult task even when done by eye on a small sample of spots, we first grouped the spots into sunspot groups by proximity. Then we determined the identification of groups from one day to the next. The final step was to match spots within the group on two consecutive days using a technique which maximized the number of spot coincidences within a number of possible relative orientations (excluding rotation of the group) in a two-dimensional grid. This method turned out to be insensitive to the assumed rotation used to pick the group associations.

Altogether nearly 36,000 groups were identified on the next day, and from these 96,283 sunspots were identified as next-day returns. The method is quite conservative as is shown by the fact that only 29% of spots were defined as returning the next day, and 10.5% of the groups seen the following day contained no spots defined as returns.

The spot group and individual spot rotation rates discussed in this paper are sidereal rates.

5. Results

The spot group rotation rate determined for the whole data set is:

$$\omega = 14.393\ (\pm 0.010) - 2.946\ (\pm 0.090) \times \mathrm{Sin}^2 B \text{ deg day}^{-1},$$

where B is the heliographic latitude. For all spots we obtained

$$\omega = 14.522\ (\pm 0.004) - 2.840\ (\pm 0.043) \times \mathrm{Sin}^2 B \text{ deg day}^{-1}.$$

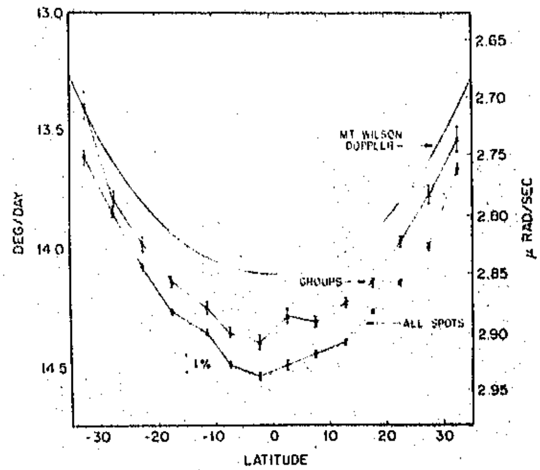

Fig.1. Rotation rates for all sunspots and for sunspot groups are plotted for 5-degree latitude zones. These results refer to the interval 1921 to 1982. Also plotted is the Doppler sunspot rate determined from the Mount Wilson data for the interval 1967 to 1982 (Howard et al., 1983), corrected for a small dispersion error (Snodgrass et al., 1984). The Doppler data are plotted from the smooth series expansion.

Figure 1 shows the rotation rate of sunspots and groups as a function of latitude. Also shown for comparison is the Doppler rate determined from the Mount Wilson magnetograph data for the interval 1967-1982 (Howard et al. 1983).

For the largest sunspots (area > 15 millionths of the hemisphere) the rotation may be expressed

$$\omega = 14.282\ (\pm 0.018) - 2.636\ (\pm 0.169) \times \sin^2 B \text{ deg day}^{-1}.$$

For medium sized spots (5 < area < 15)

$$\omega = 14.439\ (\pm 0.010) - 2.616\ (\pm 0.088) \times \sin^2 B \text{ deg day}^{-1},$$

and for the smallest spots (area < 5)

$$\omega = 14.549\ (\pm 0.005) - 2.869\ (\pm 0.051) \times \sin^2 B \text{ deg day}^{-1}.$$

The rotation rates of the sunspots of various sizes as a function of spot size are shown in Figure 2.

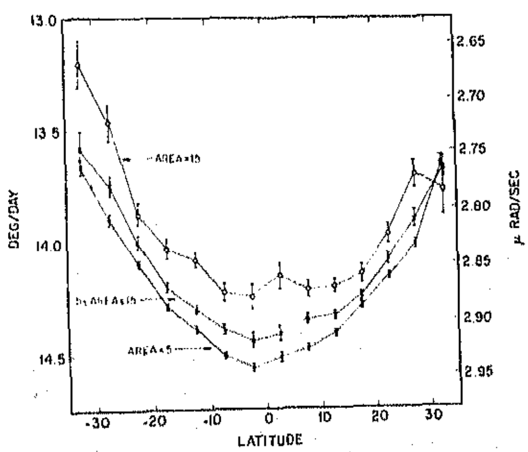

Fig.2. The rotation rate of spots of various sizes as a function of latitude. The zones are 5 degrees in width.

Variations of the average sunspot rotation rate are seen which correlate with phase in the activity cycle. There is strong peak in rotation near sunspot minimum and a weaker peak near sunspot maximum. A similar pattern is seen in Mount Wilson Doppler rotational velocity data, which is available starting in 1967. There are at times small phase shifts between the peaks seen in the two data sets.

The amplitude of the sunspot rotation variations is about 0.5% day^{-1} or about 3-4% of the average equatorial rotation rate. The amplitude of the Doppler variations is nearly double that value: 0.6 - 0.7 deg day^{-1}, or 4-5% of the average equatorial rate.

6. Discussion

The variation of rotation rate with spot size is a puzzling result. Ward (1966) found a similar result for spot groups of various sizes using the Greenwich data. The difference between the largest spots and the smallest spots in this study is nearly 2%. One possible explanation for this effect is that all spots rotate at the same rate at some depth where they are linked to sub-surface flux ropes, but that the larger spots experience more viscous drag than do the smaller spots due to their larger cross-section as they move through the photospheric plasma. We tested this hypothesis by examining rates during years when the spot-plasma rate difference was large and years when this difference was small. We could find no significant difference between the rotation rate differences of large and small spots in these two samples. This implies either that viscous drag is not a significant factor in determining the rotation rates of sunspots or that the viscous drag is the same for spots of all sizes.

In recent years there has been some debate about whether or not the sunspots and the photospheric plasma rotate at the same rate. Although this analysis does not give new results concerning the Doppler rates, it does not make it evident that the plasma cannot rotate at the same rate as all the spots.

In absolute terms, our rotation rate for spot groups is about 1% slower than that found by Ward (1966) and coincides closer than 0.1% with that found by Newton and Nunn (1951). The reason for these agreements is that Ward's results refer to all spot groups from positions that were not area-weighted (Greenwich). These results, therefore tend to be influenced by the smaller spots, which, as we found, rotate faster than the larger spots. Newton and Nunn used single-spot groups, which tend to represent large spots. Since our group positions are area-weighted, they represent the rotation of the largest spots, hence the agreement with Newton and Nunn is good.

The cycle-related amplitude variations of the sunspot rotation rate imply periodic angular momentum exchange with deeper layers in the sun. This exchange cannot take place with other latitudes at the solar surface because such large amplitude fluctuations are not seen in the Doppler data (Howard, 1976). Nor can the momentum be exchanged with the gas above the photosphere, because the inertia of this material is so low. We presume that the magnetic flux tubes of the spots are linked to deeper layers which share more or less in the same phase the variations seen in the photosphere. Alternatively the deeper layers at which the spots are linked may show no variations, and the surface rate of the spots may be determined by the drag imposed by the surface plasma.

In any case the rotation variations may be considered to represent yet another mode of torsional oscillation of the sun. These motions represent a somewhat higher amplitude torsional oscillation than those discovered earlier (Howard and LaBonte, 1980; LaBonte and Howard, 1982). The sun seems easily excited in torsional modes.

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DISCUSSION:

SIVARAMAN: When the spot is near the limb there will be foreshortening. This could result in the over estimation of longitude by more than 1/2°. How did you take care of this?

HOWARD: We did not measure spots that were more distant than 60° from the central meridian.

SIVARAMAN: You need torsional oscillations to explain your spot rotation. How will this fit in with the rotation rate above the sunspot zone?

HOWARD: From the Doppler measure we find that the high latitudes share in the rotational modulation of the sunspot zones.

GOKHALE: Is the variation of the rotation of spot groups in agreement with torsional oscillation from Dopplergram?

HOWARD: No. The effect described has an amplitude several times that of the torsional oscillation. We have made a preliminary search for the torsional oscillation effect in our data with no success.

BAGARE: Would it be possible to study from your data, the occurence of retardation in proper motion of the spot groups as reported by Waldmeir?

HOWARD: Probably yes, we have to analyse the data in order to look for these.

VINOD KRISHAN: Is the missing penumbrae of some of the spots due to the overlapping of different spots in a sunspot group?

HOWARD: I don't believe that the reason for missing penumbrae is known for certain. It is most likely due to the magnetic configuration within the spot group, which may or may not involve a nearby sunspot.

BALASUBRAMANIAM: Is there any correlation between the area of the spot and the latitude? How do you account for areas of merging spots? Once the merger/coalition starts, is there any relation between the merger time and rotation rate?

HOWARD: We have not looked for such an effect yet. When comparing the position of individual spots from one day to the next, we allow only one agreement for a spot. Thus, when we try to lineup second of the merged spots on the next day, there is no spot to associate it with. We have not studied this aspect as yet.

ALEEM: Could you please explain the modern method of measuring the area of sunspot?

HOWARD: Our techniques is designed for speed of measurement rather than accuracy. We place the cross-hair of our measuring instrument at two positions, which are digitized and stored for later analysis. These two positions are chosen so that 1) one arm of the cross-hair points to the disk center and 2) the area of the quadrilateral defined by the two cross-hair positions approximate that the sunspot umbra. We estimate our accuracy as about 30% for a single umbral measurement.