DOPPLER OBSERVATIONS OF SOLAR ROTATION

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(NASA-CR-162886) DOPPLER OBSERVATIONS OF SOLAR ROTATION (Stanford Univ.) 11 p HC A02/MF A01 CSCL 03B

N80-21238

Unclas

G3/92 46717

Office of Naval Research
Contract N00014-76-C-0207

National Aeronautics and Space Administration
Grant NGR 05-020-559 and Contract NAS5-24420

National Science Foundation
Grant ATM77-20580

SUIPR REPORT No. 804

March 1980

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Submitted to: THE ASTROPHYSICAL JOURNAL LETTERS

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Abstract

Daily observations of the photospheric equatorial rotation rate using the Doppler effect are made at the Stanford Solar Observatory. These observations show no variations in the rotation rate that exceed the observational error of about one percent. The average rotation rate is indistinguishable from that of sunspots and large-scale magnetic field structures.

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It is commonly believed that sunspots and other solar magnetic structures rotate about 5% faster than the material of the photosphere as observed through Doppler shifts (Howard and Harvey 1970; Livingston and Duvall 1979; Howard et al. 1979; see the review by Howard 1978). Recent observations at the Stanford Solar Observatory challenge this belief and yield the result that the rotation of magnetic structures and the photospheric material is the same.

Earlier Doppler observations of photospheric rotation rate showed a daily variation as large as 10% or more. These variations were assumed to be random, and the average value of these rather large variations was assumed to be the rotation rate of photospheric material, yielding the result described above.

In the observations during May, June and July 1979 described here the day-to-day variation in Doppler rotation rate was about 1%, and the average value was the same as that reported by Newton and Nunn (1951) for sunspots. We suggest that the earlier observations may have contained undetected systematic errors tending to decrease the observed Doppler rotation rate, so that it was not appropriate to simply average the observations.

Our observations are made with a Babcock solar magnetograph consisting of a vertical telescope with focal length of 6.5m feeding a vertical 22.8m Littrow spectrograph. The spectrograph is used in the 5th order with a reciprocal dispersion of 12.9mm/Å at 5250Å. The entrance aperture consists of a 6mm square mask, and image slicer, and a 0.75mm x 100mm slit. The magnetogram/dopplergram scan is made by stepping the image to fixed positions and integrating for 15 seconds at each location, instead of a continuous motion. The scan is made in east-west lines (on the sun) stepping 90 arc seconds between integration with 180 arc seconds between lines. The aperture is 180 arc seconds square and is oriented parallel to the entrance slit which is north-south in the room. The effective position of this rather large aperture is corrected for limb darkening, with the maximum correction being 4 arc seconds, since only points within the inner 3/4 of the radius of the disk are used.

The velocity observations are made by measuring the position of the spectral line with a pair of slits using the usual solar magnetograph techniques. The rms variation due to spectrograph seeing, electronic noise, and servo errors is typically 10m/s for a 15 second observation. The velocity calibration is measured each day as part of a series of automatic checks, however, since the uncertainty in the daily measurement of dispersion is larger than the variation, a constant value is used for the data reported here.

Before the observed line position data can be interpreted as motions of the sun, the relative motion of the observatory and the sun must be removed. The Doppler shifts resulting from the earth's rotation and orbital motion are removed for each point observed using the method described by Howard and Harvey (1970) and by Howard et al. (1979). Spectrograph drifts during the observation are removed by making a pair of 5 minute integrations at center of the disk, one before and one after the scan. It is assumed that the drifts are linear in time and these two disk center averages are used to define the zero line.

Howard and Harvey (1970) described the solar rotation by:

$$\omega = a + b \sin^2 B + c \sin^4 B + \text{other terms,} \qquad (1)$$

where ω is the angular velocity, b is the heliographic latitude, and a,b, and c are to be found from a least squares or other fit to the data. We have chosen to represent the rotation rate in m/s rather than radians/s because the observed quantity is a line-of-sight velocity, and some of the systematic errors are shifts in the apparent wavelength. We use the same form for differential rotation as above, but we make the assumption that the terms b and c have the same value. There is a computational problem resulting from the non-orthogonality of the terms used to describe rotation (Duvall and Svalgaard 1978; Stenflo 1977). The effect of this is that noise in the data will shift the amplitude between the b and c terms. Since the time averaged values of b and c are about the same when (1) is used to determine rotation, it is assumed here that b equals c.

Since the observed quantity is the line-of-sight component of velocity, and since rotation results in a purely azimuthal motion, the correction factor $\cos B \cdot \cos B_o \cdot \sin L$ is used where B_o is the heliographic latitude of the disk and L is heliographic longitude measured from disk center. Thus, the relation used to express rotation has the form:

$$V = (e + b \cdot \sin^2 B \cdot (1+\sin^2 B) \cdot \cos B \cdot \cos B_o \cdot \sin L + p \cdot \sin B \qquad (2)$$

The coefficient e, b, and p in (2) are found for each scan by the method of least squares with each of the data values weighted by the intensity corrected for limb darkening. This weighting helps insure that an occasional cloud will not adversely affect the results. Once the coefficients above have been found, the error in the position angle can be found from:

$$p_{err} = \tan^{-1}(p/e)$$

and the equatorial rotation velocity is found from:

$$a = \sqrt{e^2 + p^2}$$

In practice p_{err} has been found to be small with a typical value of 0.1 degree. In addition to the terms a, b, and p_{err} found above, a term a_o is found from a second fit to the data with the term b replaced with a constant -300m/s.

For the observations reported in this letter, the scattered light off the limb was about one part in a thousand so that no correction for scattered light was necessary.

Figure 1 shows the result for solar rotation obtained during May, June and July 1979. The average equatorial rotation velocity during this interval with no correction for scattered light is 2016 +/- 13m/s. The equatorial rate from sunspot observations reported by Newton and Nunn (1951) is 2020m/s. Thus, the observations reported in this letter yield the result that the day-to-day variations in the equatorial rotation measured with Doppler shifts are at most about 20m/s, and that the average rotation rate for the photosphere is indistinguishable from the Newton and Nunn (1951) rate for sunspots.

Observations beginning in May 1976 are available at the Stanford Solar Observatory. Many of the earlier observations contained appreciable amounts of scattered light. When this scattered light is corrected for (Scherrer et al. 1980) the same value of equatorial rotation rate and day-to-day variations is obtained. This yields the further result that there are no trends during these years exceeding one percent.

Acknowledgements

This work was supported in part by the Office of Naval Research under Contract N00014-76-C-0207, by the National Aeronautics and Space Administration under Grant NGR05-020-559 and Contract NAS5-24420, and by the Atmospheric Sciences Section of the National Science Foundation under Grant ATM77-20580.

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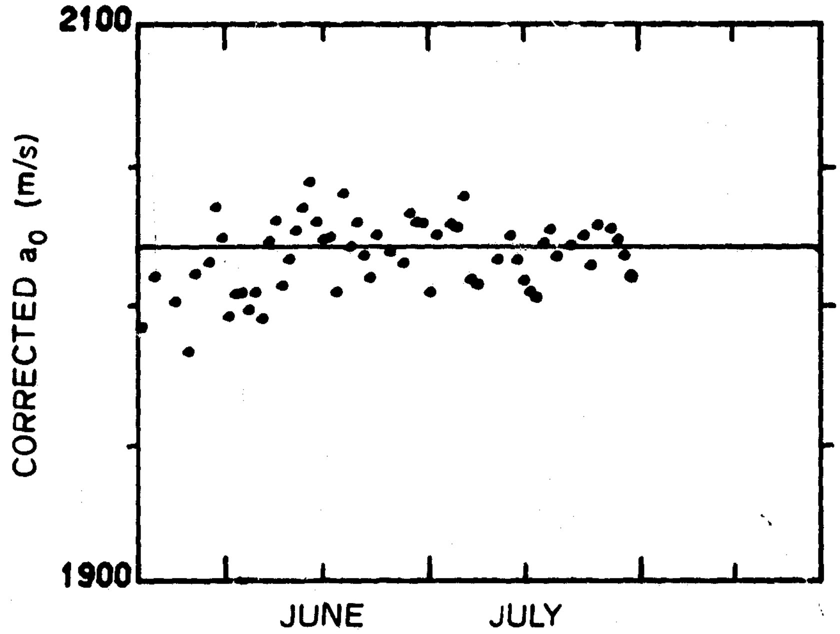

Fig. 1 Equatorial rotation velocity observed using the Doppler effect during May, June and July 1979. No correction for scattered light is necessary. The horizontal line is drawn at the Newton and Nunn rate of 2020 m/s. The simple mean of the data shown is 2016 m/s with a standard deviation of 13 m/s.