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III. SOLAR ROTATION

(Robert F. Howard)

1. *Spectroscopic Studies*

The study of solar rotation using the Doppler effect in solar spectrum lines continues to be an active and fruitful area of research. Duvall (1982) has confirmed a slower rotation rate for the photosphere than for sunspots, which bears on an earlier controversy regarding this point between the Stanford Solar Observatory and some other observatories. The issue is not settled, however.

The analysis of Doppler data has been discussed by Kubicela and Karabin (1983), who have proposed a new vector formulation for the reduction of solar disk data, including the effects of the Earth's orbit on the velocity signal. Snodgrass *et al.* (1983) have discovered an error in the calibration of the Mt. Wilson velocity signal which resulted from an error in the published wavelengths of the solar spectrum lines that have been used in calibrating the observations. This error, which was present in the Stanford Solar Observatory data as well, resulted in an over-estimate of the rotation velocity in all earlier published results from these observatories of 0.55%.

A comprehensive summary of the Mt. Wilson Doppler rotation results starting in 1967 was published by Howard *et al.* (1983). This work gives the rotation rate and latitude dependence over the time interval in one-rotation averages. Other characteristics of the large-scale velocity fields are also listed in this paper.

Balthasar (1983) has analyzed the depth dependence of the solar rotation rate using 63 Fraunhofer lines observed with the Fourier transform spectrometer at the National Solar Observatory in the visible region of the spectrum. He finds, in agreement with other observers in earlier years, that the rotation rate is slightly higher at higher elevations in the solar atmosphere. This result still remains a puzzle, with no theoretical explanation.

The rotation rate of a faintly discernible pattern of polar velocity field — large-scale cellular pattern centered on the pole — ith a rotation period of 30 days was found in Doppler observations by Cram, Durney, and Guenther (1983). This is the first evidence of any such pattern. This interesting result, which would have profound implications in the study of interior structure and dynamics, deserve verification and further study.

Variations with time of the Doppler velocity signal were the topic of a study by Kuveler and Wöhl (1983). These authors detected a decrease of nearly 2% in the equatorial rotation rate of the Sun between 1981 and 1982, in agreement with unpublished results from other observatories. The variations seen on a daily basis and the absolute value of the rotation are not in such good agreement between the various sites. Evidently instrumental effects affect the daily determinations of rotation rate significantly at most or all observatories. To what extent long-term averages of rotation rate are affected by instrumental effects is not yet known. The measurement of the rotation rate of the Sun by spectroscopic techniques is still a very uncertain process, and systematic errors are evidently not yet totally negligible.

Perez-Garde *et al.* (1981), using the λ6301.5 line of Fe I, found a large-scale velocity pattern during a few days in September 1978 between +48° and −30° with a period of about 45° in longitude. They also found an equatorward meridional flow with an amplitude of about 20 m/sec. This meridional motion is opposite in direction to that found previously at other observatories. This is another indication that measurements of small wavelength shifts in the solar spectrum may be plagued by errors of an unknown nature. These authors found an equatorial rotational velocity of 2.881 rad/sec.

Snider (1983), using an atomic beam resonance scattering technique for the λ7699 line of potassium, found an equatorial rotation rate in the interval 1979 to 1982 of 13.8 − 0.2°/day sidereal. There were no significant variations in this rather low rate. These observations were made at two sites — Oberlin and Mt. Wilson.

2. *Rotation from Tracers.*

Considerable interest in recent years has centered on the rotation of sunspots. The extensive Greenwich data set has been much utilized in several studies of sunspot motions. These data have several important advantages: They are quite homogeneous, they cover long periods of time, and there are very few missing days. A conspicuous disadvantage of the Greenwich data set is that it contains information on sunspot groups onl — t least in recent times. Group areas and positions are tabulated in the Greenwich data, but individual spot characteristics are not available, except for the case of single-spot groups, which are not typical of either groups or individual spots. Often investigators have not stressed this distinction.

Among the studies using the Greenwich data is that of Arevalo *et al.* (1982). In this analysis, it was found that the rotation rate of groups was higher in the interval 1874 to 1902 than in the interval 1940 to 1968. Furthermore, meridional flows as seen in spot group motions were northward in cycle 12, while in cycle 13 they were southward.

The positional correlation of Greenwich spot groups and high-speed solar wind streams has been studied by Balthasar and Schössler (1982). In general, an anticorrelation between these quantities is observed, strongest at the post-maximum phase of the cycle. Consecutive pairs of cycles show conspicuous similarities in this respect, which led the authors to conclude that there is a tendency for activity to occur in preferred longitudes. It is known that high-speed solar wind streams tend to originate at coronal holes, so it may be that this result is to some extent a matter of definition. Coronal holes tend to avoid active regions (and therefore sunspots) so one would not expect to find a positive correlation between the two features.

Two groups (Godoli and Mazzucconi 1983; Tuominen, Tuominen, and Kyröloinen 1983), using the Greenwich data, find the same rotational latitude shear seen in the velocity maps showing torsional oscillations. These results are barely above the noise level, and further confirmation would be desirable. This is a very important issue, because the nature of the torsional oscillation is still undefined. If these small-amplitude motions are shared by the strong photospheric magnetic fields, then this gives us more information on the depth of the oscillations.

Other investigations using the Greenwich data in this interval include that of White (1982) on the velocity dispersions of single spots (groups). He found that the velocity dispersion does not vary with latitude, is twice as large in longitude as in latitude, and is smaller for smaller spots. Kopecky (1982) has listed the high-latitude spot groups $\geq$ 40) for the interval 1874 to 1976 from the Greenwich data. Tang (1981) has studied high latitude spots in the interval 1978 to 1979 for rotation rate and finds a slightly slower rotation rate at the high latitudes than predicted from the Newton and Nunn (1951) formula. A similar result was found by Landman and Takushi (1981) using data from 1966 to 1968. They found high latitude rotation in agreement with the Newton and Nunn result from the years 1934 to 1944.

The 17th century records of Scheiner and Hevelius have been examined (Yallop, *et al.* 1982) for rotation information. These authors find no significant difference in rotation rate from modern times. A similar result was found by Abarbanell and Wöhl (1981).

The Mt. Wilson white light photographs from 1921 to 1982 have been measured for positions and areas of all sunspots (Howard, Gilman, and Gilman 1984). Individual sunspot positions have been matched with data from the following day to obtain returns of the same sunspots. In order to do this a computer algorithm had to be devised to match the pattern of sunspots on consecutive days. Thus, for the first time, rotation rates and latitude drifts of individual sunspots could be derived on a massive scale over a long time interval. One of the first results to come from this

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study was that the largest spots rotate more slowly by several percent than the smallest spots. This may represent a different depth at which the magnetic fields of large and small spots are linked. Using the same data set, Gilman and Howard (1984) discovered a systematic variation of the rotation rate of sunspots with phase in the solar activity cycle. A slight rise in the rotation rate is detected at solar minimum, and a smaller and less well-defined increase is seen near solar maximum. In the interval 1967 to 1982, for which there are Doppler velocity data for solar rotation from the Mt. Wilson magnetograph, the Doppler-determined rotation rate of the Sun shows a similar twin-peaked behavior. An increased rotation rate at minimum was found by Rovithis (1982) using Greenwich data for the 18th cycle (1945-54), who also found a slight difference between the rotation rates of the north and south hemispheres, with the north being slightly faster. Arevalo *et al.* (1982), from an examination of Greenwich spot group data over several early sunspot cycles, show a plot with a twin-peaked cyclic variation of spot rotation similar to that found in the Mt. Wilson data.

Another long set of non-Greenwich data is that of Kanzelhohe. Lustig (1982, 1983) used data from 1947 to 1979 to study the rotation rates of individual sunspots. He found that group types H and J, which are larger than group types C and D, also have slower rotation rates. Using individual spot data, Lustig determined that the differential rotation gradient declined slightly during the interval. Also, he found that the equatorial rotation rate is slightly faster during minimum than during the maximum years.

Another study of individual spots is that of Koch, Wöhl, and Schröter (1981). They determined that the rotation rate of any one spot was remarkably constant in time but that different spots differed in their rotation rates significantly.

Ternullo, Zappala, and Zuccarello (1981), using spot groups observed at Catania, found that young spots rotate faster than old spots. It is possible that this is the same effect as the size-rotation correlation discussed above. The older spots tend to be larger and rotate slower than the smaller spots, which don't live as long. It is not easy to determine which is the important factor in this case. Judging from the results of Koch *et al.* (1981) described above, it seems most likely that individual spots do not change their rates as they age. Whether or not they change rotation rate as they change size is an open question.

Magnetic Field Rotation

A special type of tracer is the weak magnetic field pattern seen in solar magnetogram observations. Snodgrass (1983) has examined the Mt. Wilson daily magnetic data covering 1967-1982 and used a cross-correlation technique in narrow latitude zones to determine day-to-day differences in longitude corresponding to the rotation rate of the patterns. The result is a rate remarkably constant with time and agreeing well with the Newton and Nunn (1951) value near the equator. At higher latitudes, where sunspots are scarce, the magnetic pattern results agreed well with the Mt. Wilson Doppler results. The errors in these determinations varied from 0.1% at low latitudes to 1.1% at very high latitudes. The cycle-related variations seen in the spot and Doppler results are not seen in the magnetic field data.

4. *Rotating Distortions*

Dicke (1982) has suggested that earlier observations of the figure of the solar limb, which showed a cyclic variation with a period of close to 12 days, result from the rotation of the solar core distorted by a strong magnetic field. Dicke calculates that such a field would experience a torsional oscillation within a period of years. Libbrecht (1984) has made more recent observations of the shape of the solar limb with an improved version of the instrument first used by Dicke and his collaborators. Libbrecht's observations were made at a much better site than the original set, and they show no more than the distortion expected by a reasonable extrapolation of the surface rotation; moreover they show no significant rotating distortion. Solar oscillation data (reviewed in Sec. II above) presently give conflicting results about whether there is rapid rotation in the deep solar interior.

5. *Torsional Oscillations*

Some further work was carried out in this interval on torsional oscillations of the Sun. LaBonte and Howard (1982) used the latitude zone Doppler velocity data to search for the torsional oscillations. This method does not depend on the latitude series solution for the rotation, so it is not subject to possible influence from the choice of terms in the latitude expansion. Using the latitude-strip data only, the torsional oscillations may be seen, although against a rather noisy background. Another feature that shows up in this plot (Figure 8 of the LaBonte and Howard paper) is a one-cycle-per-hemisphere torsional wave which is characterized by a faster rotation at high latitudes near solar minimum and a faster rotation at low latitudes near solar maximum. The amplitude is roughly that of the traveling torsional wave, i.e. $\sim 5\text{m s}^{-1}$. The high latitude portion of this pattern was found earlier by Livingston and Duvall (1979).

There is evidence for a 1/2 cycle–per–hemisphere oscillation in a comparison of equatorial rotation rates determined from north and south data separately (Howard *et al.* 1983). The amplitude is comparable to those of the two modes mentioned above.

The cyclic variation of the rotation rate of the Sun determined from sunspot and Doppler data discussed above is essentially another mode of torsional oscillation. In this case, the amplitude is about 200 ms^{-1}, which is much larger than the other modes.

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IV. SOLAR GRANULATION

(R. Muller)

During the period 1981-1984, major developments have been made in the analysis of the shape and shifts of photospheric lines used as a diagnostic of the convection in the outer layers of the Sun. The first three-dimensional numerical simulation of the solar granulation has been developed, and it is able to reproduce with some success most of the observed morphological and spectroscopic properties of granulation. It is becoming clear that the properties of the solar granulation are variable over the solar cycle. Many questions remain to be solved; further progress will rely heavily on expected improvements of the spatial resolution of the observations and the availability of larger computers.

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