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SOLAR ROTATION, 1966–1978

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Abstract. Photospheric and chromospheric spectroscopic Doppler rotation rates for the full solar disk are analyzed for the period July, 1966 to July, 1978. An approximately linear secular increase of the equatorial rate of 3.7% for these 12 years is found (in confirmation of Howard, 1976). The high latitude rates above 65° appear to vary with a peak-to-peak amplitude of 8%, or more, phased to the sunspot cycle such that the most rapid rotation occurs at, or following, solar maximum. The chromosphere, as indicated by Hα, has continued to rotate on the average 3% faster than the photosphere agreeing with past observations. Sources of error are discussed and evaluated.

1. Introduction

During the 12 year interval July, 1966 to July, 1978, spectroscopic measurements of solar rotation have been obtained on an intermittent basis at Kitt Peak. The original aim was to detect any N–S difference in rotation rates corresponding to the rather extreme N–S asymmetry in solar magnetic fields that persisted for several years over the rising portion of cycle No. 20. No such asymmetry was seen (although we will rediscuss the evidence herein). Next we attempted to find a height gradient in rotation through the photospheric layers. None was detected (Livingston and Milkey, 1972), although we did confirm an older result that the chromosphere rotates faster than the underlying photosphere. To date a total of 209 full disk records have been acquired, all made with the same instrument and reduction technique. In this paper we inspect these observations for evidence of temporal variability, particularly a variability in phase with the solar cycle.

Compared to the extensive Mt. Wilson file on solar rotation the Kitt Peak work is meager indeed. Instead of daily recordings, we have averaged 6 per year. Because small scale velocity fields on the Sun tend to mask the rotation component, continuous synoptic coverage is desirable. Nevertheless the Kitt Peak data does, in certain ways, supplement the more extensive Mt. Wilson work. Mt. Wilson observers have been constrained to use Fe 5250.2 because magnetic and velocity fields are observed at the same time. Fe 5250 shows a large limb effect (i.e. shows a systematic red shift toward the limb) which makes it somewhat difficult to trace the rotation component near the Sun's poles. The low scattered light and higher effective resolution of the McMath Telescope is an asset for work near the poles.

We will present evidence that the polar rate fluctuates in phase with the activity cycle, while the equatorial zone rate has secularly increased over the last decade. The latter phenomenon is not obviously coupled with the 11 year cycle.

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One of the most pressing problems of solar rotation concerns the reality of the observed short term variability (Howard and Harvey, 1970). Previously we have supposed that surface velocity fields were mainly responsible (Livingston, 1969). Below we will demonstrate that spectrograph seeing is largely the culprit behind variability within single day intervals. Unfortunately we still cannot address the question of variability on the scale of days or weeks.

2. Technique

A. INSTRUMENTATION AND OBSERVING PROCEDURE

All observations are made with the dual-channel magnetograph on the 13.5 m Czerny–Turner vertical spectrograph (Livingston, 1968). This system is fed by the main image of the McMath Telescope, focal length = 88.24 m (82.46 m after 1973). The image is focused at the entrance slit (width 0.40 mm, length 5.00 mm). Scanning is in heliographic parallels of latitude neglecting the curvatures introduced by the inclination of the rotation axis toward the observer and solar declination $\neq 0$. For solar latitudes $-60° < \theta < +60°$ an integrating lens is placed 3.5 m in front of image focus. This lens averages surface detail over an area of approximately 1×1 arc min or $3\overset{\circ}{.}$ of latitude. At latitudes above 60° the lens is removed. To avoid 'aperture' effects caused by limb darkening across the entrance slit a spinning dove prism can be placed above the slit. The spin rate is 3600 rpm, which is fast compared to the integration time. The image is scanned at ~40 arc sec s^{-1} in 5° increments of latitude θ. At each value of θ two scans are made: W → E and E → W, thus minimizing the effects of any monotonic spectrograph drift. Above $\theta = 60°$, the scans are made in 4 mm increments which corresponds to $\Delta\theta \sim 1\overset{\circ}{.}5$ at $\theta = 60°$.

In the focal plane of the spectrograph are a pair of double exit slits centered on the two Fraunhofer lines of interest. For each line light is fed from both wings to photomultiplier tubes. The difference signal from these PMTs serves as an error signal to a tipping plate servo which keeps the line centered on the exit slits. Coaxial to this plate is a microsyn angle readout device which generates the relative Doppler signal. DC offsets in the servo, which could masquerade as a limb effect, are removed by inserting and removing a neutral density filter while adjusting the amplifier zero point to give no Doppler change. As the microsyn output is subject to thermal drift, it is calibrated hourly by incrementing a coaxial precision engraved dial ±5° in 1° steps. Usually the drift is found to be negligible.

A Fabry lens forms an image of the grating on the PMT photocathode. It is found that the focus of this lens is critical in the red to avoid yet another form of limb effect arising from change of residual image structure projected on a non-uniform photocathode.

The magnetograph has dual independent channels so that two spectrum lines can be observed simultaneously. Generally one full disk scan is made, utilizing Hα 6562 Å and Fe 5233 Å to derive chromospheric and photospheric rates. Other lines have been employed from time to time for various reasons (see Appendix A), but herein we have combined the measures from all photospheric lines. Each full disk set takes about an hour. The microsyn signals are recorded on strip charts and, optionally, on magnetic tape by a Varian 610 computer.

B. REDUCTION PROCEDURE

From the known scan rates, solar ephemeris data for the date, and strip chart speed we calculate the solar diameter in inches $D_\odot$. We assume $D_\odot$ chromosphere = $1.0072 D_\odot$ photosphere. A least-square solution to the microsyn calibration response yields a full scale value (5 inches of paper width) in degrees of tilt $Y°$. For a given scan across the sun we fit by eye a straight line to the microsyn signal, finding the distance X of the full scale intercepts. Obviously disturbed portions over active regions are ignored. (Admittedly this is a rather subjective step. We take the view, however, that any errors of judgment affect the final result but little as the records are noisy anyway and considerable averaging is required to arrive at a significant result. Test cases of least-square fitting by computer codes yield similar answers.) This fitting is done for both W→E and E→W scans which are then averaged to yield $\bar{X}$. Then we say the sidereal rate for that latitude is

$$\omega_{\mathrm{SID}} = \left(\frac{Y° \times D_\odot \times K}{\bar{X}} + 1 \right) \text{deg day}^{-1}.$$

The constant K is different for each wavelength and channel. It includes such factors as spectrograph dispersion (assumed time invariant), tipping plate optical displacement sensitivity, and the Doppler effect law. The added 1 converts synodic to sidereal rate, assuming $360/365 \sim 1$ plus a negligible orbital component. Finally we assign to each scan the meridian value of latitude $\theta \pm B_0$, where B_0 is the heliographic latitude of the disk center. The error consequences of the various assumptions and procedures will be discussed in the Appendix B.

3. Results

Figure 1 displays the photospheric rates, north and south hemispheres combined, with the data divided into latitude zones. The error bars have the usual meaning of representing the variance (reduced to probable error) of the represented sample. The uneven time intervals which we have plotted arise in an attempt to equalize the number of observations for each entry (see Table I).

A linear regression analysis of the equatorial rates indicates a $3.7 \pm 0.7\%$ increase over the past 12 years. This confirms to a remarkable degree a similar finding by Howard (1976) based on the Mt. Wilson files. We are at present, in 1978, at about the same part of the activity cycle as we were in the fall of 1966. In July 1966 we were on the ascending leg of cycle 20 with a smoothed Zürich sunspot number $R_Z = 50$. The spring of 1978 finds us with $R_Z = 78$ and on the ascending leg of cycle 21. Although

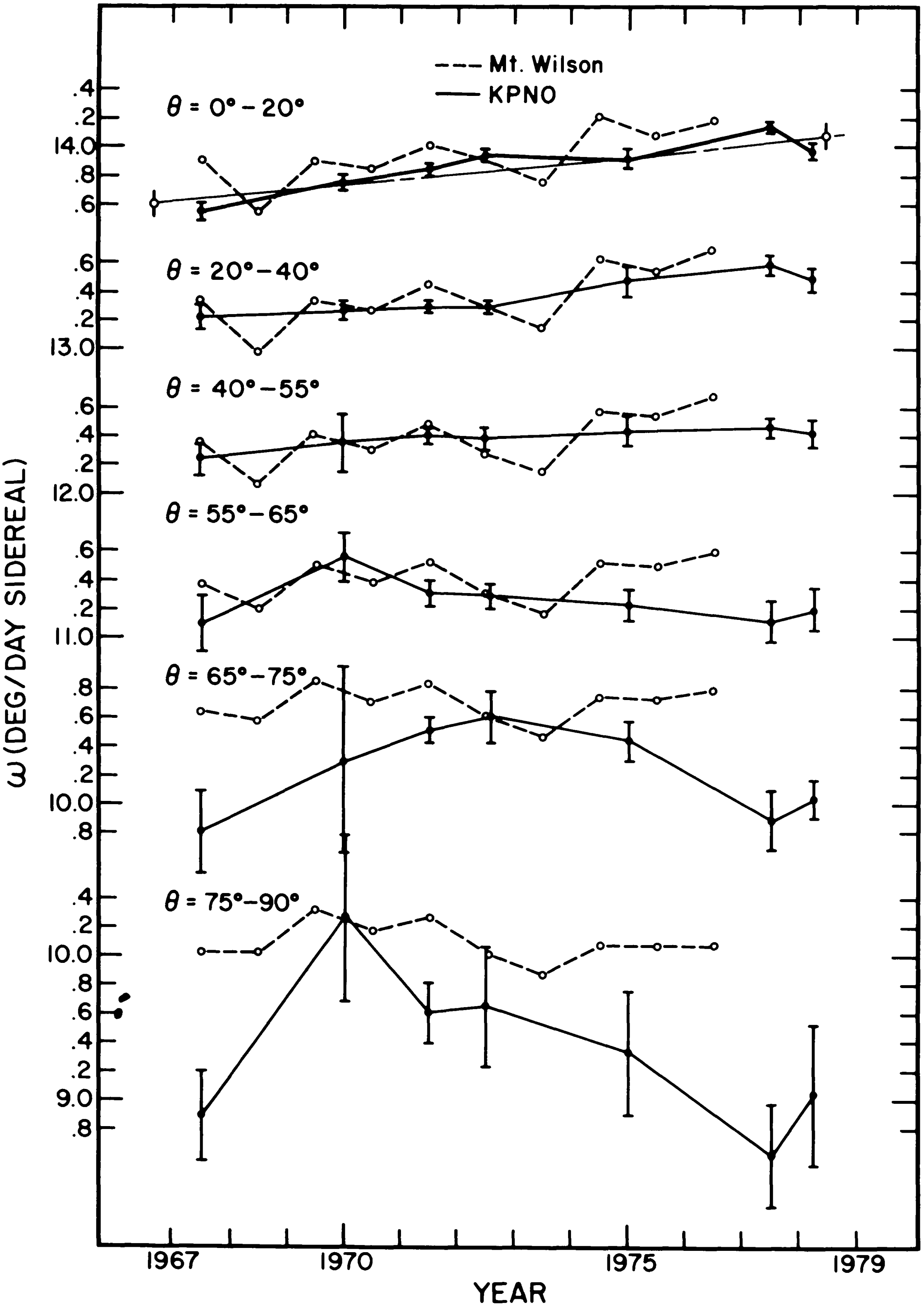

Fig. 1. Observed Kitt Peak rates by latitude zones, north and south combined, and for time intervals containing equal sample numbers. A linear least-square fit to the equatorial rates over the 12 year time span is denoted by the broken line. The Mt. Wilson data differs in that it is for yearly periods.

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TABLE I

Summary of observed photospheric and chromospheric rates $-20° < \theta < +20°$

	Photosphere		Chromosphere		$\Delta\omega$
Epoch	Number of days	ω_{SID} deg day^{-1}	Number of days	ω_{SID} deg day^{-1}	(chromo – – photo) (%)
1966–68	17	13.53 ± 0.07	10	14.45 ± 0.15	6.6
1969–70	16	13.74 ± 0.05	22	14.73 ± 0.26[a]	7.1
1971	22	13.82 ± 0.04	9	14.43 ± 0.21	4.4
1972	16	13.92 ± 0.04	12	14.10 ± 0.18	1.3
1973–76	24	13.90 ± 0.06	9	14.16 ± 0.14	1.9
1977	26	14.11 ± 0.04	18	14.45 ± 0.13	2.4
1978	14	14.01 ± 0.07	—	—	—

[a] Includes Ca^+ K 3933 data.

there is a suggestion of a turn over, the mean rates are presently 3.7% higher than in 1966–68 and we tentatively must conclude that this observed increase in equatorial rate is not related to the 11 year cycle.

At high latitudes the situation is different. In particular at $65° < \theta < 75°$ the data strongly hints at being periodic with a maximum rate at, or following, sunspot maximum. Between $75° < \theta < 90°$ the effect is even more pronounced (~8%) although less certain. The growth of the error bars at high latitudes is a consequence of the scanning lengths being reduced (but the size of small scale perturbing velocity fields remaining fixed, of course). An inspection of the data from 75° to the pole showed no evidence for a solar polar vortex, in agreement with Beckers (1978).

Figure 2 is designed to display any N–S rotational asymmetry. If we omit the observation of 6 January 1967, there is a hint that in 1966–68 the northern hemisphere rotated faster by $2 \pm 1.6\%$. This is of interest because over this time period there was markedly more magnetic activity in the north (White and Trotter, 1977). Note that Howard and Harvey (1970) find no difference between equatorial rates determined for north and south separately.

Table I also summarizes our Hα data; two trends are noticed. First the differential rotation with height is greatest at solar maximum (1969–70) and least at minimum. Second, if the photospheric rate had *not* undergone its secular increase this height gradient would appear periodic. Instead the gradient falls short of having returned in 1977 to the earlier 1966 level.

4. Discussion

The two main results of these observations are that the photospheric equatorial rotation rate has increased by 3.7% over the interval 1966–78, and an apparent solar-cycle related variation of the photospheric rotation rate occurs at latitudes greater than 65°. The variation of equatorial rate is in complete agreement with the

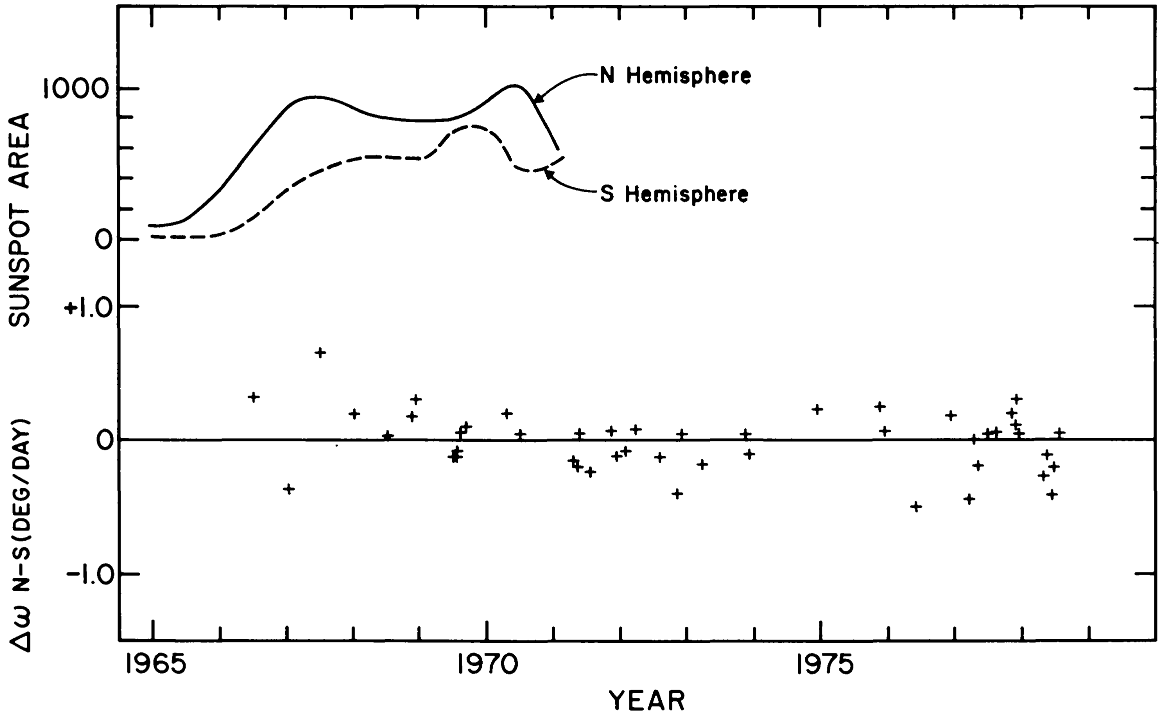

Fig. 2. Difference between the north and south equatorial rates over the 12 year interval. Each plotted point is the average over a day, or adjacent days when applicable. The sunspot data is from White and Trotter (1977) which unfortunately stops in 1972.

results of Howard (1976). With the benefit of two additional years of data (1977–78), we conclude that there is no obvious connection with the 11-year sunspot cycle. The equatorial variation is presumably a surface effect, as it has been shown (Newton and Nunn, 1951) that the rotation rate of sunspots did not vary significantly over five sunspot cycles. This assumes that the sunspots are the tracers of the rotation rate of a more massive subsurface layer in which the magnetic fields are rooted. The surface layer affected by the rotation change should be at least as thick as the supergranular layer, as the mixing of this layer is very rapid.

The high-latitude variation of rotation rate derived from the present observations is not seen in Howard's (1976) results. The points in Figure 1 for Howard's data are derived from his published values of a, b, c, where the rotation rate is fitted to an expression $\omega = a + b \sin^2 \theta + c \sin^4 \theta$ (θ = heliographic latitude). These values of a, b, c may not be representative of the rotation rate at very high latitudes. According to Howard and Harvey (1970), in the full-disk least-square solution used to derive a, b, c on a daily basis, data within 20″ of the limb are excluded. Near the poles, 20″ corresponds to an average latitude of 78°, so that data above this latitude do not contribute to the analysis. The full-disk least-squares solution for a, b, c weights each point on the disk equally. There are many more points at low-latitudes than high and so the values of a, b, c may not adequately represent the rate at latitudes $\theta > 65°$. Consequently the results of Howard (1976) do not preclude the variation of high latitude rotation reported in this paper.

What connection does the high latitude rotation variation have with the solar cycle? Another cycle-related variation observed at latitudes >65° is the polar field strength. The solar wind, coupled to the Sun via the magnetic field, is thought to exert a torque on the Sun of $\sim 10^{31}$ dyne cm (Hundhausen, 1972). Near solar minimum, much of this torque is probably exerted at high latitudes (Schatten, 1973; Duvall *et al.*, 1979), thereby introducing a solar-cycle variation in the torque at high solar latitudes. We may estimate the amounts of angular momentum in the supergranular layer to see if the time-varying solar wind torque could be effective in varying the high-latitude rotation rate. The supergranular layer is assumed to be 5000 km thick. We employ the outer convective zone model of Böhm (1963) and the rotation rate was assumed constant at $\omega = 2\ \mu\text{rad s}^{-1}$. Under these assumptions, the angular momentum of the volume of gas polewards of 65° latitude in one hemisphere was found to be 8.4×10^{39} erg s. If we assume that half of the solar wind torque acts on this volume of gas for one year, a depletion of 2% of the angular momentum is found. Acting over four years, 8% of the angular momentum would be lost, which is approximately the variation observed.

There are some problems, however, with a model of this type; the layer depth assumed is critical. With a choice of 7000 km instead of 5000 km the model is no longer tenable due to the rapid increase of density with depth. Also, there must be minimal interaction between the layer in question and deeper layers. Current solar models predict that an outer layer much thicker than the supergranular layer is unstable to convection. Convective mixing would preclude the ability of the solar wind torque to cause significant solar rotation variations. Nevertheless, without a more complete knowledge of the subsurface convection, such a model cannot be excluded.

Eddy *et al.* (1976) propose that during the Maunder Minimum differential rotation was enhanced. The fact that our high latitude angular rates are lowest in proximity to the time of solar minimum, implying increased differential rotation, is in qualitative agreement with Eddy *et al.* (1976). There is also the weak evidence from Figure 2 that a slight increase of rotation rate accompanies solar activity. Foukal (1976) similarly finds a coupling between the non-magnetic and magnetic plasma in the sense that the presence of the latter tends to speed up the former. The solar cycle behavior of the Hα data (Table I) further supports this view, assuming that at solar maximum the fraction of Hα features associated with magnetic structure is greater. The qualitative picture that emerges is that of a thin non-magnetic surface layer (Foukal, 1977) which is accelerated from below by rapidly rotating magnetic structure and decelerated from outside by solar wind braking, with the effectiveness of these opposing forces varying with the solar cycle.

We emphasize that our 'chromosphere' rates are derived from either the core of Hα or the K_3 feature of Ca^+ 3933. The cores of Mg 5173 and Mg 5183, to which Athay (1976) assigns a height range of 600–400 km, i.e. middle-low chromosphere, yield normal photospheric rotation rates. Thus, when Wiehr (1978) using Ca^+ 8498, or Schröter and Wöhl (1976) using Ca^+ 3933 K_{232}, report slower rates, we assume that the discrepancy originates from the difference in the heights of formation of the line profiles being sensed. (Alternatively the discrepancy may arise because we are comparing magnetic tracers, such as the Ca mottles, with motions of the non-magnetic atmosphere.)

5. Summary

Over the past 12 years the photospheric rotation rate has steadily increased by 3.7% near the equator, while at high latitudes $\theta > 65°$ the rate appears to vary in a systematic way, being higher at solar maximum than minimum by ~8%. As reported in the past the Hα chromosphere continues to rotate faster than the photosphere by 1.5 to 7%. The amplitude of this effect may be solar cycle dependent. As shown in the Appendix our technique is open to many sources of error, but all are <1% except spectrograph seeing which can, in the winter, be ~2%. Nevertheless our sampling method removes the low frequency component of seeing so that day-to-day rate variations cannot be ascribed to this noise source.

For a restricted range of convection zone models the observed character of rotation variation can be explained by the braking action of the solar wind as it ranges from polar origin (near minimum) to lower latitudes (at maximum). The cause of the 3.7% secular increase in equatorial rates is unexplained.

Appendix

A. SPECTRUM LINES EMPLOYED

As mentioned in Section 2 a variety of Fraunhofer lines have been used for our rotational measurement (see Table II). Taking into account the exit slit width and its position along the line profile, the effective height of origin of all lines is similar for the purposes of this study. The exceptions are the cores of Hα and Hβ, and the K_3 component of Ca^+ 3933, which we designate as chromospheric indicators. Many of our early rotation measurements were made using Fe 6569, but the presence of a strong terrestrial water vapor blend in the blue wing of this line negates these results, which are excluded in the present analysis.

Compared to other photospheric lines we find the cores of the Mg lines (λ 5173 Å and 5183 Å) show a relatively small limb effect and thus, by our methods, they simplify polar observations. Similarly if narrow slits are used in the core of Fe 5233 the limb effect is reduced and this line becomes also useful for polar observations.

B. ERRORS AND THEIR CONSEQUENCES

In this section we list and evaluate where possible the sources of error in our rotation measurements. First we consider the observational errors and then errors related to assumptions and procedures in the reduction process.

TABLE II

List of measured spectrum lines with representative exit slit arrangements

	Number of records	Slit width[a] mÅ
Photospheric		
CN 3881.65	3	22–16–22
Fe 3890.85	3	22–16–22
Fe 3943.35	7	
Fe 4841.79	1	
Ni 5155.13	2	65–45–65
Fe 5164.55	6	
Fe 5232.95	55	175–150–175 50–40–50
Fe 5250.21	20	65–45–65
Fe 5324.19	2	
C 5380.32	4	
Fe 5397.62	4	
Fe 5905.68	1	
Na 5895.94	1	
Fe 6569.22	7	
High photospheric (low limb effect)		
Mg 5172.70	8	50–40–50
Mg 5183.62	7	50–40–50
Chromospheric		
Ca^+ K 3933.68	5	
Hβ 4861.34	1	
Hα 6562.81	70	220–350–220

[a] Blue wing – core separation – red wing.

The recognized observational errors are:

Scattered Light – A potential weakness of the spectroscopic method is its susceptibility to error from scattered light. Stray light from near disk center tends to dilute and lower rates deduced near the limb. Some authors consider this problem so severe as to blame most reported variance in rotation on this source (see discussion by Howard, 1978).

Scattered light in the McMath Telescope has been measured by Pierce and Slaughter (1977). In their Figure 3c they show the observed intensity as a function of wavelength 44″ from the limb for a variety of telescope conditions ranging from freshly aluminized to relatively dirty mirrors. At λ5000 Å the respective range is 0.1 to 0.5%. Because the heliostat is 140 m distant from the 1.6 m concave, it acts as a baffle against scattered light, varying seasonally as the projected aperture of the heliostat flat changes from 1.1 m to 1.7 m (winter) in its minor diameter. In winter, when the scattering is greatest, we find the effective wavelength of scattered light at the limb corresponds to a point $r/R_\odot = 0.5$ on the disk. In the worst case, then, the observed rotation rate is reduced by ~0.2%.

Scattering from cirrus and similar stratus type clouds is another matter. We find typically that cirrus which attenuates 50% reduces the deduced equatorial rate by ~5% when the usual full chord fit is made to the Doppler record. If the measurement is confined to near the limbs a reduction of ~10% is found. Thus day-to-day variability in atmospheric clarity due to the presence of aerosols, 'smog', and thin cirrus can thus be a significant source of observed changes in solar rotation rates.

Spectrograph Seeing – From time-to-time measurement reproducibility has been checked by making repeated equatorial scans. The resulting variance is always disturbingly high ($\Delta\omega/\omega \sim 1$ to 5%) and we have supposed that minor scan rate or scan path differences, the 5^{m} oscillations, or spectrograph seeing are at fault. We now will demonstrate that spectrograph seeing alone can account for most, if not all, the observed variance. On a date when the position angle of the Sun's pole was zero (7 July), the image was fixed by limb guiders so that the western terminus of the equator was just off the entrance slit. Telescope drive and guiders were then turned off allowing the image to drift across the slit. After the scan was completed, the image was rapidly returned to guider control at the west-limb and the process repeated. The scan-return-release cycle time is $2^{\mathrm{m}}\!.5$, and the observations continued for $\sim 1\frac{1}{2}$ h and after these scans a Bromine absorption tube was inserted over the entrance slit with the image centered. The grating was turned to λ 5190 Å, a spectral region where the solar continuum coincides with a solar-like Br line, and spectrograph seeing was measured ($\sigma = 38\ \mathrm{m\ s^{-1}}$). Figure 3 is a representative record of rates from such repeated scans. In this case the Doppler records have been measured in two ways: first by the usual linear fit to the entire chord of data $\sigma = 60\ \mathrm{m\ s^{-1}}$, and second using only points just inside the limbs $\sigma = 42\ \mathrm{m\ s^{-1}}$ or about the same as for the Br measures. We conclude that spectrograph seeing is the dominant noise source. The finding that limb measures are quieter than full chord measures, in this instance $\sigma_{\mathrm{limb}} = 42\ \mathrm{m\ s^{-1}}$ vs $\sigma_{\mathrm{center}} = 60\ \mathrm{m\ s^{-1}}$, consistently seems to be the rule.

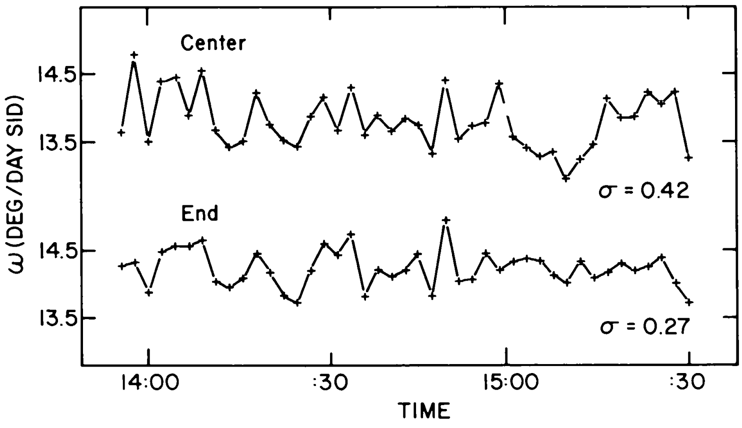

Fig. 3. Repeated observations of the equatorial rate which has been measured in two ways: 'center' indicates the usual fit by eye to the entire chord, 'end' indicates only the limb values have been used.

Spectroscopic Blends – The disturbing influence of telluric blends, mainly water vapor, on spectroscopic rotation displacements is recognized (cf. Livingston and Milkey, 1972). None of the photospheric lines employed in this study suffer from blends (except Fe 6569, data from which has been excluded herein).

The chromospheric line Hα is a problem in that several HOH lines reside in the core and there is no exit slit arrangement which avoids them all. In recent years we have settled on a (0.22–0.35–0.22 Å) window which has the advantage that there is only a single HOH line in the blue wing and this line remains inside the slit opening over the full range of rotational displacement.

Water vapor content of the atmosphere has a strong seasonal dependence in Arizona, summer being wet and winter–spring very dry. We can test whether water vapor perturbs our Hα rates by dividing the data according to these seasons. For July–August all years combined we find $\omega_{\mathrm{SID}} = 14.36 \pm 0.17$, while January–May yields $\omega_{\mathrm{SID}} = 14.22 \pm 0.13$. We conclude that while HOH blends must affect our Hα rates somewhat, the error is not significant.

Rate Errors – On occasion over the last decade rate errors traceable to equipment failure have occurred. Drive off drift scans are of course free of this error. Also, early in the program (1966–71) we measured $D_\odot$ directly on the brightness records that accompany the Doppler data and so these measures must be free of rate errors. At other times we have made spot checks of measured vs calculated $D_\odot$ and found agreement. However there are periods of time when rates have not been verified and rate errors may have gone undetected.

Spectrograph Dispersion – Spectrograph dispersion enters as a linear factor within the reduction constant K. Minor instrument modifications have led to 2.5 cm inconsistencies in setting the camera focus, focal length = 1350 cm. The resulting error is $2.5/1350 = 0.2\%$ – negligible.

Temperature, pressure and humidity fluctuations alter the refraction index of the air in the spectrograph and this, in turn, the dispersion. Using Edlén's (1966) formulae we find $\Delta T = 10\,^\circ\mathrm{C} \rightarrow \Delta d = 4(10^{-7})\%$; $\Delta P = 10$ mm Hg $\rightarrow \Delta d = 2(10^{-7})\%$; Δhumidity p–25% $\rightarrow \Delta d = 4(10^{-8})\%$. The thermal expansion of the grating blank (Boro-silicate glass) alters the ruling spacing: $\Delta T = 10\,^\circ\mathrm{C} \rightarrow \Delta d = 3.2(10^{-3})\%$.

Microsyn Drift – Electronic gain changes and a non-zero thermal coefficient to the microsyn device itself are possible contributors of error. In practice, from the variance of the calibration factor Y°, we find warm up time is 30^{m} and thereafter the angle sensitivity is constant within 0.2%.

The recognized reduction errors are:

Neglect of variation of the inclination of the solar rotation-axis to the Earth–Sun line – Because the solar equator is inclined to the ecliptic plane by 7.25°, all rotation measurements are too small by the factor $\cos B_0$, where B_0 is the heliographic latitude of disk center (Kubicela and Karabin, 1977). The factor $\cos B_0$ varies during the year between 1 and 0.992. The correction for this effect has not been applied to the data discussed here and results in possible errors of 0.8% in rotation rates.

Neglect of the variation of the Earth's orbital velocity correction during the year – The largest correction applied to the data to derive solar rotation rates is for the varying projection of the Earth's orbital velocity across the solar disk. An average correction of 1° day^{-1} has been applied to the rotation rates discussed here. The contribution of the orbital velocity actually varies during the year due to the change in orbital velocity, varying earth–sun distance, and the variation of the projection of the ecliptic onto the solar disk. A calculation was made of the yearly variation of the correction due to these three effects, with the result that the assumed 1° day^{-1} correction actually varies between 0.96° day^{-1} and 1.04° day^{-1}. This causes uncorrected errors in the rotation rate of ±0.04° day^{-1}, or ±0.3% of the equatorial rate.

No correction for the Earth's rotational velocity – No correction has been applied for the diurnal component of the Earth's rotation velocity. Because at each solar latitude we make a pair of scans in which the solar image is traversed in opposite directions, the effect of the Earth's rotation velocity is reduced to negligible proportions.

Variation of heliographic latitude along a scan chord. Because of the inclination of the solar rotation axis to the line-of-sight is not 90°, the curves of constant heliographic latitude are not straight lines on a projected solar image. For the present study the latitude at central meridian was used as the latitude representative of a given chord. However, if the north pole is tipped toward the Earth, in the northern hemisphere the 'central meridian latitude' is lower than the mean latitude of a given chord. Coupled with differential rotation, this effect yields an error in the reported rotation rate, which we estimate to be a maximum of 0.04° day^{-1}. Averaging over north and south, the effect should approximately cancel out.

TABLE III

Error summary

Source	Error
Scattered light	
instrument	−0.04 to −0.2%
sky	0 to > −10%
Spectrograph seeing	
($\Delta t = 2^{\text{m}}$)	<1.5%
Telluric blends	0
Telescope rate error	normally 0
Spectrograph dispersion	
thermal expansion of grating	$\Delta T = 10°\,\text{C} \rightarrow \Delta d = 0.003\%$
refractive index of air for ΔT, ΔP, Δ humidity	negligible ($<10^{-6}$ %)
Microsyn drift	<0.2%
Neglect of cos B_0 projection effect	<0.8%
Neglect of variation of Earth's orbital velocity	±0.3%
Neglect of curvature for constant θ-locus	±0.003%

Table III summarizes the above error discussion. Providing cirrus and thin clouds are avoided we find no sources of error which exceed 1%. A possible exception arises from spectrograph seeing, but this effect cannot account for day-to-day or other long term variations.

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