MEASUREMENT OF KODAIKANAL WHITE-LIGHT IMAGES

II. *Rotation Comparison and Merging with Mount Wilson Data*

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Abstract. Sunspot umbral positions and areas were measured for 82 years (1906–1987) of daily, full-disk photoheliogram observations at the Kodaikanal station of the Indian Institute of Astrophysics. The measurement technique and reduction procedures used were nearly identical to those used earlier for the reduction of Mount Wilson daily full-disk photoheliograms, covering an overlapping interval of 69 years. In this paper we compare the differential rotation of the Sun from the analysis of the Kodaikanal data with the Mount Wilson results. In addition, we analyze the data set formed by combining the data from the two sites for differential rotation. While doing this, it has become apparent to us that small, subtle optical effects at both sites produce systematic errors that have an influence on rotation (and other) results from these data. These optical effects are analyzed here, and corrections are made to the positional data of the sunspots from both sites. A data set containing the combined positional data of sunspots from both sites, corrected for these optical aberrations, has been constructed. Results for both sunspot groups and individual sunspots are presented. It is pointed out that optical aberrations similar to those found in the Kodaikanal data may also exist in the Greenwich photoheliograph data, because these two sets of solar images were made with similar telescopes.

1. Introduction

Solar differential rotation has been recognized for many years to be an important clue to the internal dynamics of the Sun and the dynamo process that causes the solar activity cycle (Dicke, 1970; Gilman, 1974). Many observational studies of solar rotation have been published from a number of observatories, but discrepancies in these various results (Howard, 1978) suggest that systematic errors may contribute to these differences. We present here an attempt to derive solar differential rotation results that take account of systematic errors and are therefore likely to be more accurate than many results published previously.

A program to measure the area and position of each sunspot umbra from the daily photoheliograms of the Kodaikanal station of the Indian Institute of Astrophysics has been completed. These photographic data extend back to 1906 in an observational series that continues to the present time. The measurement and

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digitization of these data follow the procedure adopted for the measurement of a similar data set in the interval 1917–1985, done at Mount Wilson some years ago. The instrument, the data set, the method of digitizing, and the first results from the Mount Wilson measurements were discussed in an earlier paper (Howard, Gilman, and Gilman, 1984; hereafter HGG).

In an earlier paper (Sivaraman, Gupta, and Howard, 1993; hereafter SGH) we discussed the measurements of the Kodaikanal data for a period of 35 years and presented some very preliminary comparisons of the two data sets. The agreement in the rotation rates from these data sets gave us confidence that the measurement procedures followed at Kodaikanal are identical to those at Mount Wilson. Now the Kodaikanal measurements covering the years 1906–1987 have been completed, and from these the solar rotation, rotation dependence on solar cycle, and meridional motions have been determined (Gupta, 1994). We will present these results in the next paper in this series.

It was only while attempting to compare these results with those from the Mount Wilson data (HGG) for the entire overlapping period of 69 years that it became apparent that small, subtle optical aberrations are present in the images at both of the sites, and that these are manifested as systematic differences between the rotation rates derived from the data from the two sites. Furthermore, these differences became more conspicuous when the data sets from the two sites were merged and the resulting solar rotation and meridional motions were examined.

In this paper we deal with the way we have arrived at the numerical values for the parameters that would jointly correct for the optical aberrations in the data sets for the two sites, judged by the internal agreement of the results from the merged data set, while we have reserved the actual presentation of the results from the Kodaikanal data set for the entire period of 82 years corrected for the optical aberrations to the next paper in this series.

2. Digitization of the Data and Solar Coordinate Determinations

For each site the observational data consist of daily, white-light photographs of the full solar disk. The image sizes at the two sites are comparable: at Mount Wilson the image diameter is about 16.5 cm and at Kodaikanal it is about 20 cm. Both sites have generally good early morning seeing, and the images from both sites are of comparable quality and photographic density.

The digitization was carried out at both sites with a digitizing pad (HGG). The initial reduced data set for each day for which there is an observation consists of 8 limb measurements in the X and Y coordinate system of the measuring pad, plus a position measurement in X and one in Y for each individual sunspot (umbra) that can be seen on the solar disk. These measurements, which provide individual sunspot position and area information (HGG), will be referred to below as the ‘raw’ measurements.

The final raw data set consists of a set of files, one for each year of measurement. There are 82 of these files for the Kodaikanal data (1906–1987) and 69 for the Mount Wilson data (1917–1985).

In order to convert the raw $X - Y$ measurements of sunspot positions to solar latitude and CMD, it is necessary to correct all of the position measurements of the limb and sunspots for atmospheric refraction. For the Mount Wilson data, a small correction was made for an error in the determination of the position of the polar angle of the Sun at the telescope during part of the interval. This is also described in HGG. This error was estimated from the behavior of the measured meridional motion of the spots, which is sensitive to the axis alignment – more so than the sunspot rotation which is determined from the same data.

The corrected limb positions are used in a least-squares solution for a circle, and then sunspot latitudes, CMDs, and areas are calculated from the sunspot measurements, using the usual geometrical method (Smart, 1977). All areas are converted to disk center areas. Then sunspot groups are defined by the proximity of individual sunspots (HGG). The positional criteria for membership in the same sunspot group are 5 deg in heliocentric longitude and 3 deg in latitude.

Thus the second set of files, one for each year, consists of heliocentric positions and umbral areas of individual sunspots and, separately, positions and total umbral areas of sunspot groups. Group positions are area-weighted, using the areas of the individual sunspots. Observation dates and times are also included in each record as fractional day numbers.

3. Determination of Rotation and Meridional Motions

Using the second data set described above, it is possible to determine the motions of individual sunspots and sunspot groups. But first it is necessary to identify which group and which individual spot in one observation is to be identified with a group or spot in the previous observation.

In the case of sunspot groups, the identification is relatively simple. Groups are defined by the proximity of individual spots, as described above, and there is little ambiguity in identifying the group in a subsequent observation, except for those rare cases where one group splits into two in the next observation (using the proximity limit employed to define a single group), or where two groups merge into one.

Identifying 'returns' of individual sunspots on the next observation, that is, identifying which are the same sunspots in the next observation, is a much more difficult problem than identifying returned sunspot groups. There are uncertainties in this process, even when it is done by eye by an experienced observer. The process used for the Mount Wilson data set earlier was explained in the earlier paper (HGG). It has been modified since that time to include more criteria to determine an identification of a group return than just the number of returned sunspots in the group. The criteria now are the average individual sunspot position difference, the average individual sunspot area difference, the number of returned sunspots, and the group position difference (from that expected from the average differential rotation rate for groups at that latitude). These criteria are weighted, with the most weight assigned to the number of spots returned, and only a few percent of the total weight given to the spot and group position distances and less than one percent given to the area differences. This means that in practice the difference from the earlier method is small.

As in the earlier study (HGG), the criteria and the procedure for the selection of ‘returned’ sunspots on the next day are designed to be very conservative. It was considered preferable to reject some (perhaps many) returns that may have been real – thus reducing the fraction of returned spots – rather than take a chance on accepting some returns that in fact were not the same spots. Thus, these results should not be used in a determination of individual sunspot lifetimes.

Sunspot group motions in longitude (rotation) and latitude (meridional motion) are determined by calculating the longitude or latitude difference from adjacent observations and dividing by the time difference between the two observations.

Note that we do not have information on the lifetimes or ages of sunspots or sunspot groups. We do not follow spots or groups from the first sighting to the last sighting. We only have position differences on pairs of consecutive observations. This means that we often consider motions of spots or groups more than once during their lifetimes. So in what follows, a discussion of a certain number of spots or groups does not indicate that there were that many separate features, just that we had that many pairs of consecutive observations of the feature.

4. Results

In this section we discuss differential rotation results from the Kodaikanal data (using only the 69-year data base for the period 1917–1985 for which we have data from both sites) and compare them with the Mount Wilson results. For this comparison we used sunspot group data because, as discussed above, there is less chance of error in identifying next-day returns of sunspot groups than of sunspots. It will be seen that there are problems in this comparison. The equatorial rotation rates from the two sites differ by about 0.6%. This is much greater than can be explained by random errors, so we looked at possible systematic errors at both sites. We found optical problems at both sites, and we corrected the data for both sites. We present here some of the results from the uncorrected and the corrected data sets. In spite of these corrections, it is possible that there are systematic effects remaining that we are not able to diagnose at this time.

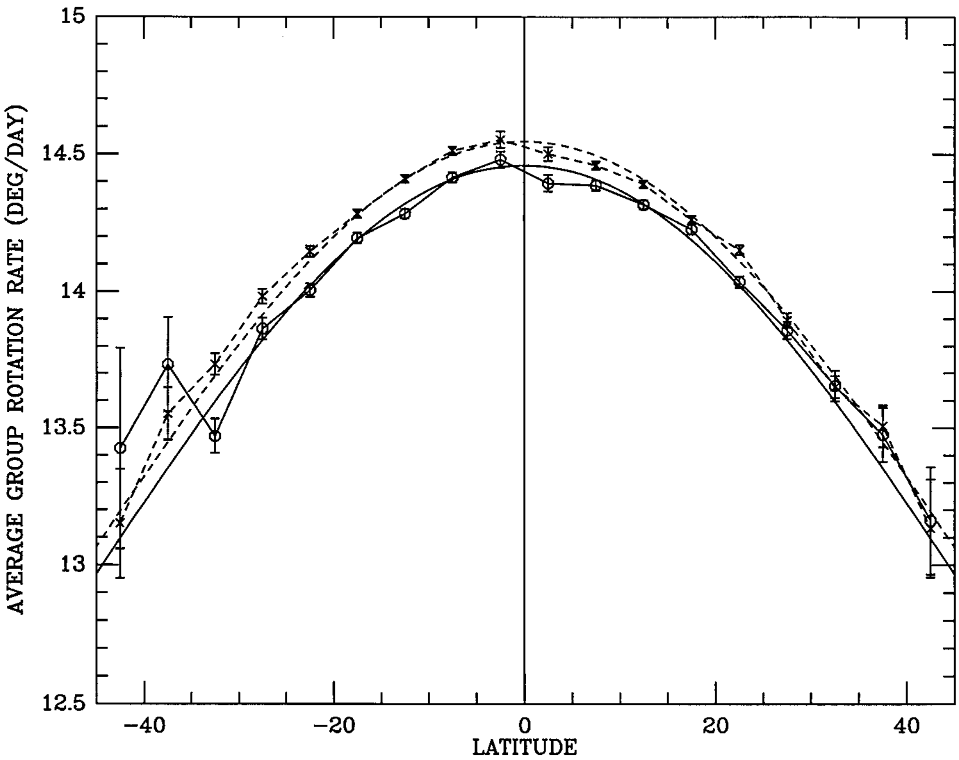

Figure 1. Separate plots for Mount Wilson (solid line) and Kodaikanal (dashed line) showing the rotation rates of sunspot groups for the years 1917–1985 in sidereal deg day^{-1} vs latitude in degrees. The smoothed solid and dashed lines are the least-square rotation solutions for Mount Wilson and Kodaikanal, respectively. These data are not corrected for the image aberrations discussed in the text.

4.1. Results from Uncorrected Data

4.1.1. *Sunspot Group Rotation Comparison*

Figure 1 shows the comparison between the rotation rates of sunspot groups from uncorrected data from the two sites. The difference shown is quite small, about 0.6%, with Kodaikanal faster than Mount Wilson. This amounts to about 12 m s^{-1} at the equator. The Mount Wilson group rotation rate is faster than that found earlier (HGG) by close to 0.5%. This discrepancy is undoubtedly due to some minor changes in the reduction procedures introduced since the earlier work, such as the new method of identifying sunspot returns, which is discussed above.

The smooth continuous line and the smooth dashed line in Figure 1, and in all such plots in this paper, represent the least-squares rotation solutions for Mount Wilson and Kodaikanal, repectively, using the expansion $\omega = A + B \sin\theta$, where θ is the latitude and ω is the sidereal rotation rate in deg day^{-1}. The values of A and B (in deg day^{-1}) for the Mount Wilson and Kodaikanal sunspot group results respectively in Figure 1 are:

$$A = 14.459 \pm 0.006, \quad B = -2.99 \pm 0.06, \quad N = 36\,655\ ,$$

$$A = 14.547 \pm 0.005, \quad B = -2.96 \pm 0.05, \quad N = 41\,029\ ,$$

where N is the number of sunspot groups in the data subset. The error bars in the unsmoothed solid and dashed lines in this and all plots in this paper represent $\pm$ one standard deviation of the mean for all the individual determinations in the interval of latitude (or, in some plots below, longitude).

4.1.2. *Other Diagnostics and Optical Problems at Both Sites*

After seeing the result of Figure 1, the analysis programs were carefully examined for programming errors. When a lengthy study of the programs failed to reveal any errors that could correct for the discrepancy seen in Figure 1, the data combined from the two sites were used to generate diagnostic plots in an attempt to find possible systematic problems. The combined data set is made by simply arranging the daily reduced digital records (each giving spot areas and heliocentric positions for one observation, as described above) in chronological order. Ideally this combined data set would contain observations approximately every 12 hr (corresponding to the longitude difference between Kodaikanal and Mount Wilson), if there were no gaps in the observations at either or both sites. Then the rotation was calculated from each two adjacent observations, if the time difference between the two observing times did not exceed 1.8 days. The great majority of time differences in the combined data set are approximately 12 hr. Refer to Figure 1 in SGH.

The first such diagnostic plot is shown in Figure 2. This is a plot of rotation vs latitude for two different subsets of the data: the first is for ‘day pairs’ where Mount Wilson is the first observation, and Kodaikanal is the second observation. We will call this data subset α. The second data subset (β) represents the cases where Kodaikanal is the first site, and Mount Wilson is the second site.

It is clear from Figure 2 that this is a powerful diagnostic. Large differences are seen between the α (solid lines) and β (dashed lines) data sets in both coefficients, A and B. Also the individual points, compared with the expansion in latitude, represent rotation that is faster in the south and slower in the north for data subset α, while for data subset β, the individual results are faster in the north and slower in the south. This discrepancy can be explained by a systematic error in one or both site data sets in the orientation of the rotation axis of the solar disk during the observation. Subsequent tests showed that this discrepancy seen in Figure 2 can be explained by a relative position angle error between the two sites of about 0.7 deg. Further tests, maximizing the number of returned individual sunspots as a criterion for the optimum tilt angle, indicated that this error should be shared between the sites as -0.4 deg for Mount Wilson and 0.35 deg for Kodaikanal, where a positive angle indicates a clockwise rotation when north is up and east is to the right.

But, after correcting for the image rotation errors discussed above, the large rotation difference between the α and β data subsets, shown by the smooth lines

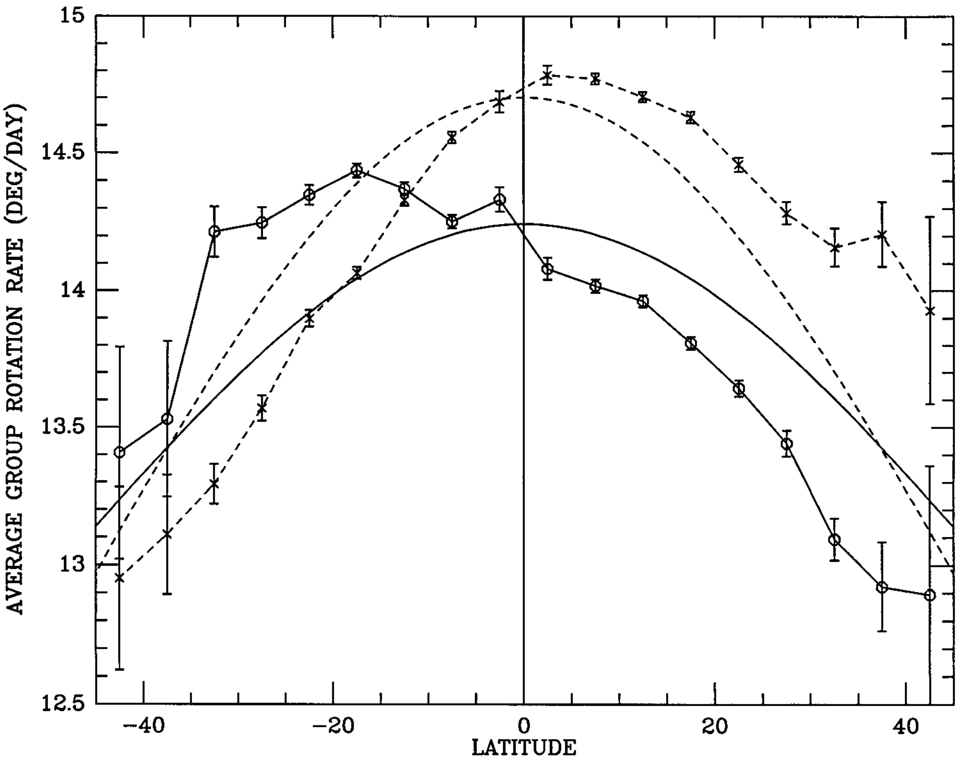

Figure 2. Rotation rates of sunspot groups in sidereal deg day^{-1} vs latitude in degrees for two data subsets α and β extracted from the full 69-year (1917–1985) combined data set. The solid lines represent the rotation rate from data subset α, where the first observation is from Mount Wilson and the subsequent observation is from Kodaikanal. The dashed line is from data subset β, where the first observation is from Kodaikanal and the next observation is from Mount Wilson (see text). The smooth solid and dashed lines represent the least-squares solutions for the two data subsets α and β, respectively. This is a diagnostic plot from data not corrected for the image aberrations discussed in the text.

in Figure 2, remained and was suggestive of some sort of distortion in one or both images. As a further diagnostic, a plot similar to Figure 2 was generated, but with central meridian distance as the abcissa instead of latitude. This is shown in Figure 3. The least-squares solutions for a straight line for data sets α and β are also shown in Figure 3. Here again we see evidence of some sort of distortion of the image.

After a lengthy and exhaustive search for causes of the discrepancies seen in Figures 2 and 3, we came to the conclusion that these problems are the result, at least in part, of two causes. These are discussed in the following paragraphs.

The Mount Wilson images before about 1965 were found to be slightly elliptical. We hypothesize that before the new, ultra-low-expansion flat coelostat mirrors were installed at the 60-foot tower telescope at Mount Wilson about this time, this

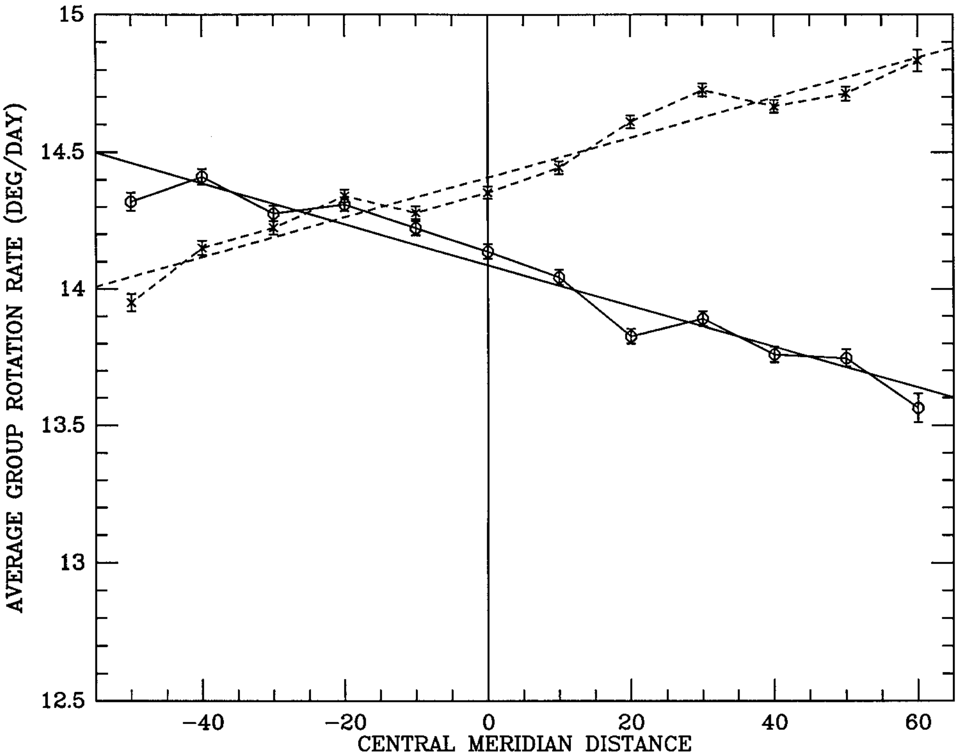

Figure 3. Similar to Figure 2 for sunspot groups, except that the rotation rates are plotted against central meridian distance in degrees.

image had errors due to some astigmatism-like aberration, compounded by random focusing errors. After the new mirrors were installed, it was found to be no longer necessary to adjust the focus daily. At this time, in 1965, the correct focus was determined by a set of focus exposures, and the focus was not changed after that. The solution to this problem in the digital positions for the earlier data was to test the measured limb points for ellipticity for each day's data. The magnitude of the ellipticity and the orientation of the major axis for each day were determined. If the ellipticity fell below a threshhold value (0.003 $R_{\odot}$), no correction was made, but for most observations before 1966, adjustments were made to the limb points and the sunspot positions, assuming in the case of the sunspots that the magnitude of the adjustment varied linearly with the distance (from the minor axis) along the major axis of the ellipse. These ellipticity corrections made for the Mount Wilson data are quite small, averaging about 0.015 $R_{\odot}$. Note that these corrections are made after the limb and spot points are corrected for differential atmospheric refraction, as described in HGG. There is no correlation between the elliptical correction and the zenith distance of the Sun at the time of the observation, so we conclude that these changes do not correct for differential refraction, which was already corrected. Kodaikanal data were also tested for ellipticity, but in almost no cases were corrections found to be necessary.

However, the Kodaikanal images were found to suffer from optical distortion (barrel distortion). This results from the fact that there is a stop in the optical path that is not at the aperture. Also, this stop results in a slight vignetting of the image. It should be noted that the Mount Wilson images do not suffer from either distortion or vignetting. The optical system at the 60-foot tower telescope at Mount Wilson is a simple, straight-through design, using a lens of 60-foot (18-m) focal length, with no enlargement, no folding, and no stops.

This is not the first time that optical distortion has been found to affect the position measurements of solar features. Beckers (1976) reported large differences between sunspot rotation results derived from spectroscopic measurements and those from proper motions determined from sunspot drawings made with the Sacramento Peak Observatory patrol instrument. Subsequently he discovered (Beckers, 1977) pincushion distortion of as much as 2 deg (heliocentric) in the image formed by the patrol instrument.

The challenge in the analysis of the data to minimize the effect seen in the diagnostic plots (Figures 2 and 3) was to find the optimum set of parameters for the amplitudes of the optical effects, including the image orientation errors mentioned above. (Another factor we considered in these trials was the latitude drift vs latitude plots similar to those published earlier for Mount Wilson (Howard and Gilman, 1986). These considerations are not discussed in this paper, but they will be covered in a later paper on meridional motions.) Unfortunately these parameters are generally non-orthogonal. After a very lengthy trial-and-error analysis, we came to the conclusion that with the effects mentioned above we could not completely eliminate the problems evident in the diagnostic plots shown above. What we present here, and what we will work with in subsequent analyses of solar rotation, and other results, is a compromise that gives a fairly good solution to the problem.

For the Kodaikanal data, the parameters finally arrived at are a correction of -0.005 for the barrel distortion, an offset of this distortion of 0.3 $R_\odot$ eastward in the direction perpendicular to the solar rotation axis and -0.1 $R_\odot$ (southward) parallel to the rotation axis. The solution for the vignetting is a correction (increase) of 0.004 $R_\odot$, made to the limb points only.

4.1.3. *Diagnostic Plots for Corrected Data*

Using the optimum values of the parameters given above, we have replotted the diagnostic plots of Figures 2 and 3. These are shown as Figures 4 and 5. These are not ideal corrections; but we were not able to find a combination of parameters that completely removed the image distortion problems. However, we are convinced, after more than 200 trials, each of which required about 24 hr of computing time, that this is the best set of parameters that we can find.

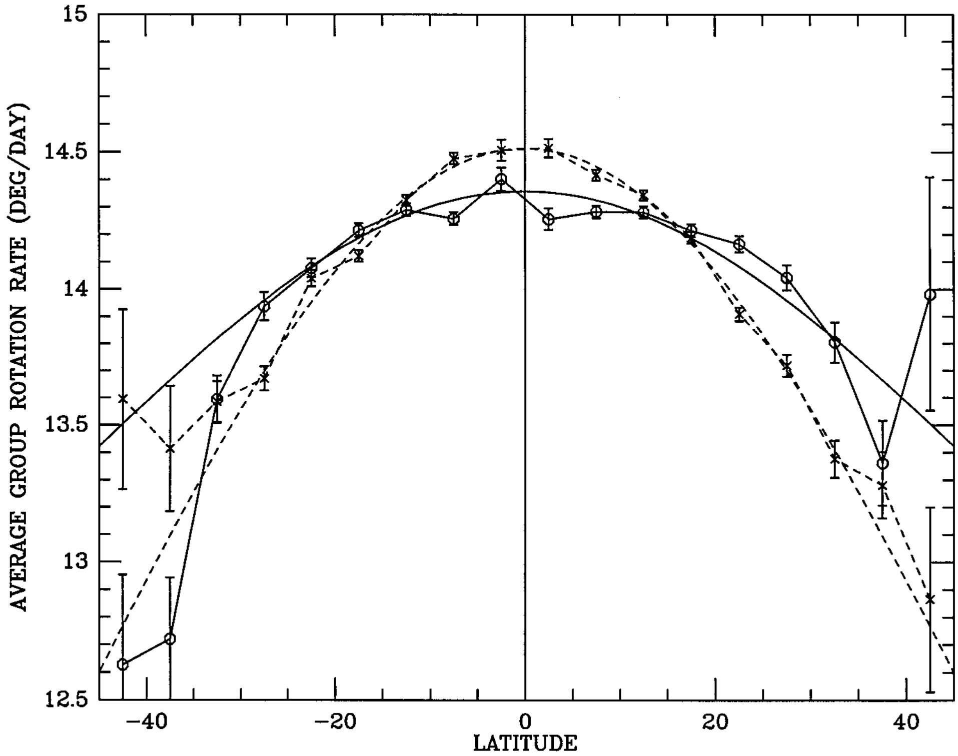

Figure 4. Similar to Figure 2 for sunspot groups, except that the image aberration corrections discussed in the text have been applied to the data.

This inability to resolve completely the remaining systematic effects evident in the diagnostic plots suggests that there may be yet another unknown source of image distortion that is still present in the data. Another explanation of this remaining error is systematic errors in the observational and/or measurement procedures at each site. In either case, the amplitude of this remaining effect is quite small. The plots *apparently* suggest a significant remaining error, but one should remember that these are *extremely* sensitive diagnostics. If one examines the plots carefully, it is clear that the remaining systematic errors are really very small. Note that 1.0 deg corresponds to about 17 arc sec at disk center. Our observations extend to CMDs of 60 deg, so, being conservative, we can adopt an average value of 15 arc sec for one degree of longitude. The quantity 0.1 deg day^{-1} then corresponds on average to 1.5 arc sec, but the ‘day’ difference is actually generally about 0.5 day, from one site to the next, therefore 0.1 deg day^{-1}, which is one tick mark on the ordinate axis of these plots, corresponds to a position error of about 0.75 arc sec. The difference between the two results at the equator in Figure 4 is less than 0.2 deg day^{-1}, but note that the sunspot group number distribution peaks around a latitude of about 12 or 13 deg, and falls off fairly sharply on either side of that position. Thus the errors for the great majority of sunspot positions are significantly smaller than that,

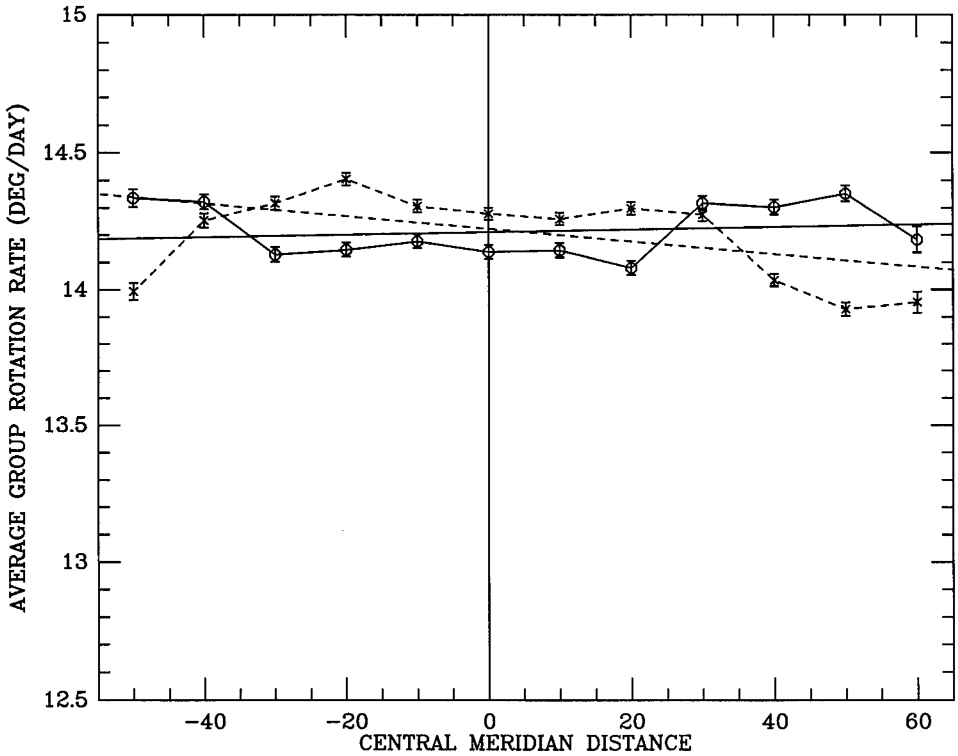

Figure 5. Similar to Figure 3 for sunspot groups, except that the image aberration corrections discussed in the text have been applied to the data.

especially if one assumes that the correct value is halfway between the two curves, so that the average error is half of the discrepancy. In Figure 5, the discrepancy is only about 0.05 deg day^{-1}, which corresponds to a systematic error of about 0.4 arc sec. So, these errors are comparable to or less than the magnitude of the seeing, but, as noted above, their systematic nature suggests some additional very small optical aberration in one or both data sets.

4.2. Results from Corrected Data

4.2.1. *Rotation Results from the Corrected Data Sets*

Figure 6 shows the differential rotation results for the corrected data sets from both sites for the full 1917–85 interval for sunspot groups. This is a corrected version of Figure 1. The values of the coefficients (in deg day^{-1}) and N, the number of groups for the best least-squares fit to these data, are:

$$A = 14.461 \pm 0.006, \quad B = -3.02 \pm 0.06, \quad N = 36\,640\ ,$$

$$A = 14.470 \pm 0.005, \quad B = -2.97 \pm 0.05, \quad N = 41\,224\ ,$$

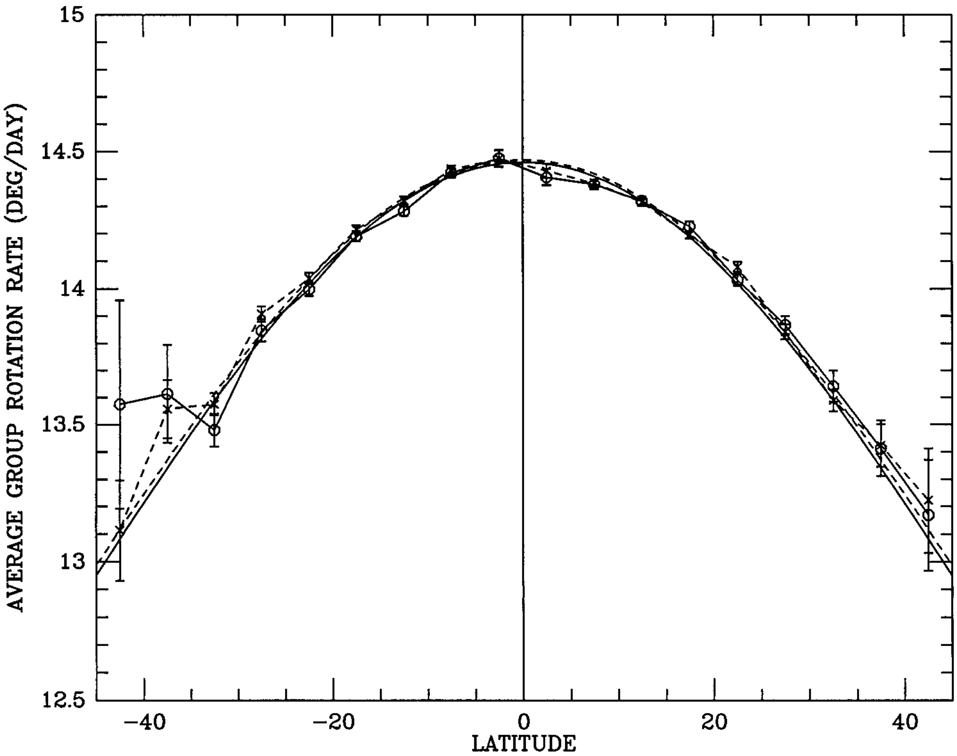

Figure 6. Similar to Figure 1 for sunspot groups, except that the image aberration corrections discussed in the text have been applied to the data.

for the Mount Wilson and Kodaikanal data, respectively. Note that the difference in the A coefficient between these two results is about 0.06%, or about 1.2 m s^{-1}.

In Figure 7 we show the differential rotation of sunspot groups for the combined data set. This includes data in chronological order from both sites, as described above. The coefficients (in deg day^{-1}) and number of groups for this data set are:

$$A = 14.449 \pm 0.005, \quad B = -2.95 \pm 0.04, \quad N = 83\,506\,.$$

This result includes 'day pairs' where Mount Wilson is the first observation and Kodaikanal is the second observation and *vice versa*. In addition, whenever there are data gaps at any one site, the day pairs include data where Mount Wilson is the first and the second observation, and where Kodaikanal is the first and the second observation. In other words, all rotation determinations are made from the next observation, whichever site it might be from, as long as the time difference between the two observations is not greater than 1.8 day.

4.2.2. *The Rotation of Individual Sunspots*

In the diagnostic work we used only sunspot group data because, as discussed above, there is little chance for error in the identification of the returns of groups

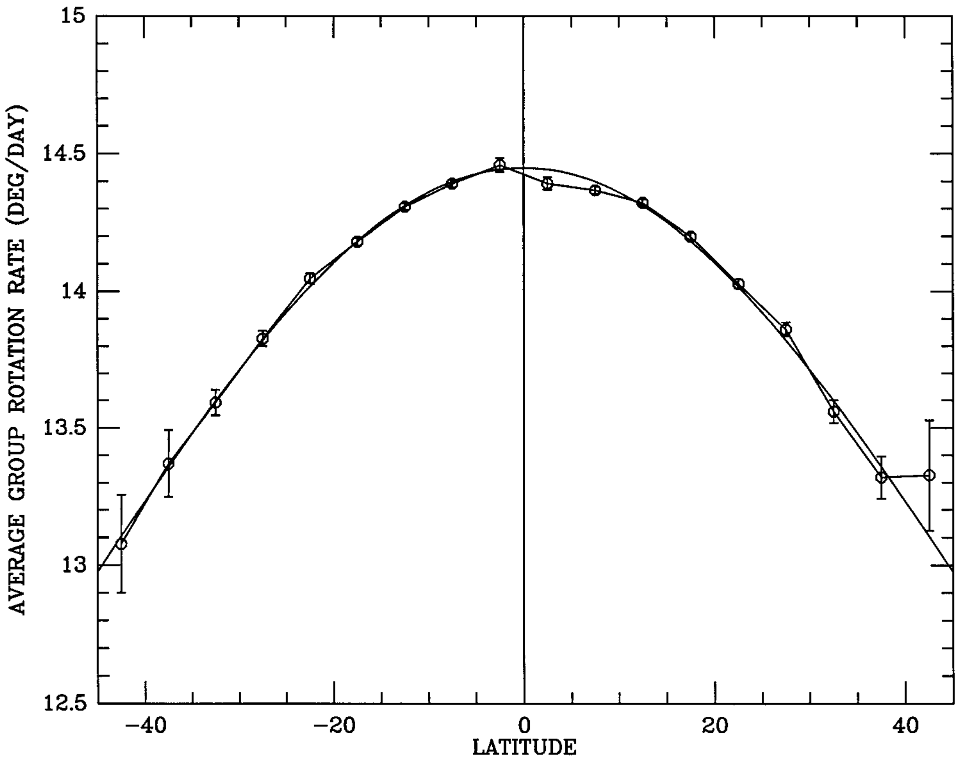

Figure 7. Rotation rate of sunspot groups from the combined Mount Wilson−Kodaikanal data set for the full interval (1917−1985). See text for details.

from one day to the next. The differential rotation of individual sunspots from the two sites is shown in Figure 8. The coefficients derived from these data in deg day^{-1} and numbers of spots are:

$$A = 14.446 \pm 0.003, \quad B = -2.78 \pm 0.03, \quad N = 110\,749\ ,$$

$$A = 14.456 \pm 0.002, \quad B = -2.88 \pm 0.02, \quad N = 113\,112\ ,$$

respectively for Mount Wilson and for Kodaikanal.

Figure 9 shows the rotation of individual sunspots from the combined data set. The values of the coefficients for this reduction in deg day^{-1} and N, the total number of spots, are:

$$A = 14.444 \pm 0.003, \quad B = -2.73 \pm 0.03, \quad N = 179\,842\ .$$

In may be noted that the value of A for the data in the combined data set is less than that for either separate site. One might expect this because the number of small, short-lived spots is greater in the combined data set (because of the 12-hr time difference), and since it is known that small spots rotate more rapidly than

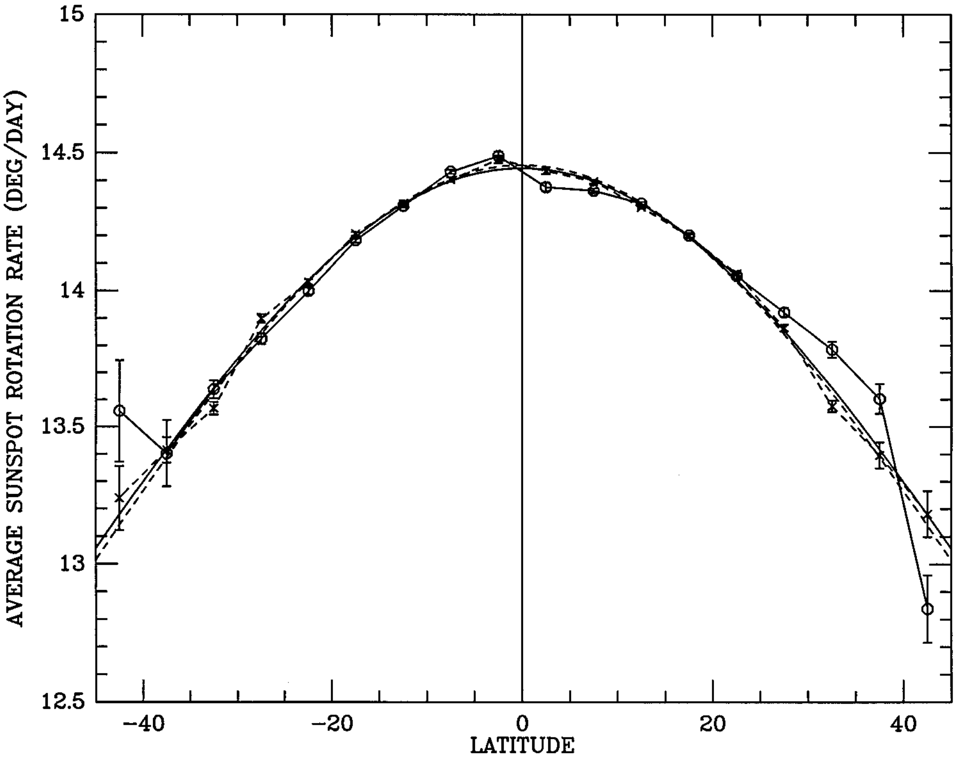

Figure 8. Rotation rate of individual sunspots from the separate Mount Wilson (solid lines) and Kodaikanal (dashed lines) data sets for the full interval (1917–1985).

large spots (HGG), we may expect a larger contribution to A from these small spots. This is yet another indication that average rotation rates are subject to systematic uncertainties from various sources.

4.2.3. *Comparison with the Earlier Mount Wilson Results*

Earlier results suggested that the average of the rotation rates of individual sunspots was greater than that of sunspot groups (HGG). The results presented here do not confirm that result, either for the combined data set or for the Mount Wilson data alone, from which the earlier result came. It is not clear why this is the case. Evidently the changes made to the reduction code over the years have introduced systematic changes in the rotation results: an increase of about 0.5% in the group rotation rate and a decrease of about 0.5% in the individual sunspot rate.

The correction for the astigmatism-like optical aberration in the Mount Wilson sunspot positions discussed above may be expected to change the rotation (and other) results from earlier published results from the same data set. In addition, there have been a number of minor improvements made to the reduction software over the years. The result is an increase of nearly 0.5% in the value of the A coefficient in the solution over the result given in HGG. The HGG result covered fewer

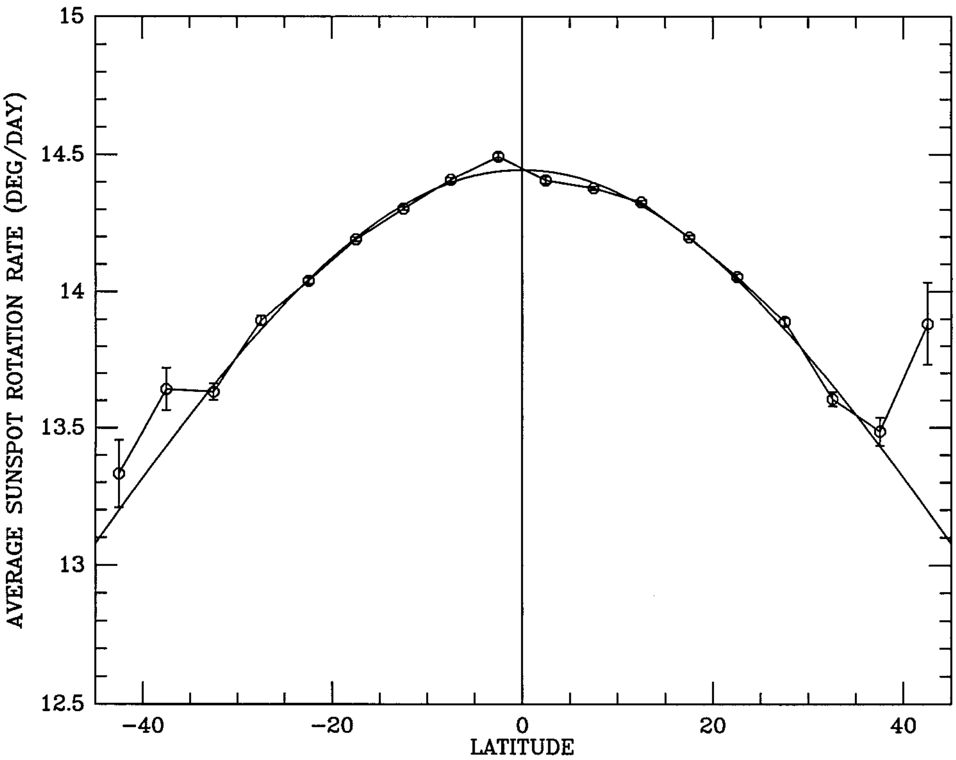

Figure 9. Rotation rate of individual sunspots from the combined Mount Wilson–Kodaikanal data set for the full interval (1917–1985).

years (62 instead of 69) than the current reductions, but this does not have a very large effect on the resulting value of A. From HGG, the values of the coefficients and the number of groups were:

$$A = 14.393 \pm 0.01, \quad B = -2.95 \pm 0.09, \quad N = 35\,823 .$$

Using only the corrected Mount Wilson data from 1921–1982 we now find:

$$A = 14.462 \pm 0.006, \quad B = -3.03 \pm 0.06, \quad N = 33\,329 .$$

Judging from the discussion given above, the determination of rotation rates from sunspot positions, or any from any tracer for that matter, has its own significant inherent limitations. The results may be strongly influenced by systematic errors of various origins. One cannot rely upon published errors (such as those given above) because they, of course, do not take into account possible systematic errors.

5. Summary and Conclusions

We have completed a large-scale project involving the measurement of many years of daily white-light photographs from the Kodaikanal station of the Indian Institute of Astrophysics. This data set has been compared with and merged with a similar data set measured some years ago at the Mount Wilson Observatory.

We may draw the following conclusions from this study:

(1) The rotation results from the two sites agree well after corrections for optical aberrations at both sites.

(2) Sensitive diagnostic tests indicate that some optical aberrations may still exist at one or both sites, but the level of the remaining errors is a fraction of an arc sec.

(3) Modifications to the reduction technique over the years since the earlier analysis (HGG) and the aberrations discussed here have changed slightly the Mount Wilson rotation results.

(4) All tracer rotation results at the level of a few tenths of a deg day^{-1} are subject to systematic errors from optical or other effects.

The data set formed by combining the measurements from the Kodaikanal and Mount Wilson measurements forms probably the most accurate and complete data set currently available for sunspot groups, and certainly for individual sunspots. We intend to use this combined data set over the next few years in order to examine other characteristics of sunspot dynamics, such as meridional motion.

Finally, we would like to introduce a note of caution based on our experience with the optical distortion described above. The Greenwich dataset, which has been used by a number of investigators, is a composite collection of solar images from four observatories: the Royal Observatories at Greenwich and Capetown, South Africa; Kodaikanal; and the Royal Alfred Observatory in the Mauritius Island. All of these observatories used identical Dallmeyer photoheliographs. The primary image from the Dallmeyer (or Thompson) objective lens is magnified to give a final solar image of 8-inch diameter, using a magnifier. These images have been corrected for atmospheric refraction, but no corrections have been made for optical distortion. Judging from the reports in the yearly *Greenwich Photoheliographic Results* and from *Astronomical and Magnetical and Meteorological Observations Made at the Royal Observatory, Greenwich in the Year* . . . for 1874–1875, corrections for image distortion were made in the early years, before about 1886, when there was no image magnification and the image was 4 inches in diameter, but after that time, no such corrections were made. It is not clear why no corrections were made for the later data, although in the report for 1927 there is the sentence: ‘The radial distortion of the lens used has been measured and found negligible.’ It is hard to believe this, judging from the distortion now known to exist from an identical instrument. However, of course, the precision achieved here in the digital measurements and reduction is greater than earlier generations of astronomers could have imagined.

At any rate, it would be advisable to measure the optical distortion in the Greenwich images (or from the Greenwich data) because of the many studies that have used these data for rotation and meridional drift results.

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