SOLAR ROTATION AS DETERMINED FROM OSO-4 EUV SPECTROHELIOGRAMS

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Abstract. Spectroheliograms obtained in extreme ultraviolet (EUV) lines and the Lyman continuum are used to determine the rotation rate of the solar chromosphere, transition region, and corona. A cross-correlation analysis of the observations indicates the presence of differential rotation through the chromosphere and transition region. The rotation rate does not vary with height. The average sidereal rotation rate is given by ω (deg day^{-1}) $= 13.46 - 2.99 \sin^2 B$ where B is the solar latitude. This rate agrees with spectroscopic determinations of the photospheric rotation rate, but is slower by ~ 1 deg day^{-1} than rates determined from the apparent motion of photospheric magnetic fields and from the brightest points of active regions observed in the EUV. The corona does not clearly show differential rotation as do the chromosphere and transition region.

1. Introduction

The differential rotation rate of the solar atmosphere relates directly to our understanding of the dynamics and interaction between the solar plasma and its magnetic field. The rotation rate has been studied principally by two methods. One is the so-called tracer method in which a feature is defined, and either its motion is measured on the solar disk or its recurrence is noted at limb passage. Tracers have included sunspots (Newton and Nunn, 1951; Ward, 1965), the photospheric magnetic field (Wilcox and Howard, 1970), localized features in the white light corona (Hansen *et al.*, 1969), and the brightest points in active regions as observed in the extreme ultraviolet (EUV) region of the spectrum (Simon and Noyes, 1972). Each of these determinations leads to a value of the equatorial sidereal rotation rate *greater* than 14.2 deg day^{-1}. The second method yields the rotational velocity by a direct measurement of the Doppler shift of photospheric and chromospheric lines. Such studies indicate an equatorial rotation rate generally *less* than 14.0 deg day^{-1} (Livingston, 1969a; Howard and Harvey, 1970), although systematic effects may be present. For instance, the metallic lines of Fe I appear to rotate at an equatorial rate of 12.8–14.0 deg day^{-1}, while the Hα line shows a rate of 13.7–14.8 deg day^{-1} (Livingston, 1969a).

Attempts have been made to reconcile the different rates by postulating the existence of large-scale irregular motions to explain the Doppler observations (e.g. see Piddington, 1971). Alternatively, these different rotation rates may in fact be real and reflect fundamental dynamical characteristics of the features or of the gas itself that are related to the interaction between the atmosphere and the solar interior (Livingston, 1969b; Foukal, 1972; Wilcox, 1972).

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In this paper we use the full-disk EUV spectroheliograms obtained by the Harvard College Observatory experiment on OSO-4 to derive the differential rotation rate. These observations offer a unique opportunity to observe the rotation of the emission patterns from transition region and coronal lines across the solar disk. This analysis used cross-correlation techniques to obtain a sidereal rotation rate at the equator of 13.46 ± 0.44 deg day^{-1}. This value agrees with the spectroscopic determinations of the rotation rate (Livingston, 1969a; Howard and Harvey, 1970).

2. Method

The data were taken from the *Atlas of Extreme-Ultraviolet Spectroheliograms from OSO-IV* (Reeves and Parkinson, 1970). The Atlas was compiled from digitized rasters acquired between 25 October and 27 November 1967 by the Harvard College Observatory scanning spectroheliometer on the OSO-4 satellite (Goldberg *et al.*, 1968). Each spectroheliogram consisted of an array of 40×48 points that covered an area 36.5′ sq centered on the Sun; the instrument aperture was 1′ sq and the detector bandwidth was 3.2 Å. Pairs of spectroheliograms were selected from the Atlas for the Lyman continuum (897, 865, 826, 800, 740, and 667 Å) and for six lines, O IV (790 Å), O VI (1032 Å), Ne VIII (770 Å), Mg X (625 Å), Si XII (499 Å), and Fe XVI (361 Å), representing a sequence of increasing height and temperature in the solar atmosphere; the pairs were separated by 1.1–3.3 day. In order to use a cross-correlation technique, we interpolated the digitized spectroheliograms along lines of constant solar latitude (from 0° to $\pm 55°$ at intervals of 5°) to generate one-dimensional arrays of points at intervals of 3.5° in longitude from the central meridian to $\pm 49°$. This longitude interval corresponded to the spatial resolution of the instrument at the center of the disk. We then computed the cross-correlation function $\varrho_{12}(u)$ be-

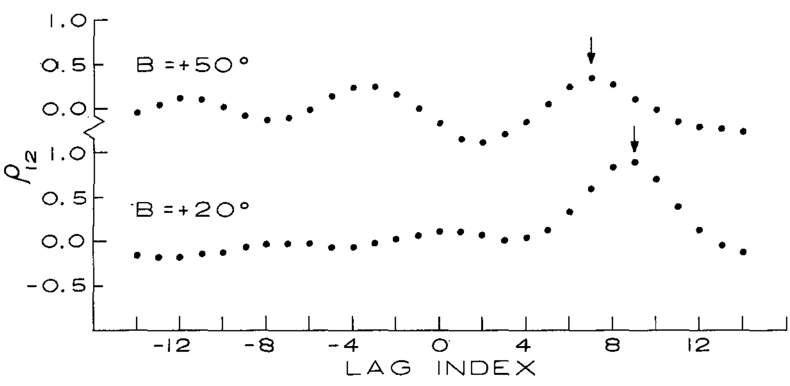

Fig. 1. Examples of cross-correlation functions at two latitudes. The two spectroheliograms that are correlated here were observed in Ne VIII (770 Å) on 26 and 28 November 1967 with a time separation of 2.50 days. The arrows indicate the position of maximum value of ϱ that determines the rotation rate. The different lag indices marked by the arrows imply a rate of rotation slower at $+50°$ than at $+20°$. The other peaks that occur in the cross-correlation for $B = +50°$ would correspond to rotation rates substantially outside the acceptable range if attributed to rotation.

tween the one-dimensional intensity arrays at the same latitude on both members of each pair of spectroheliograms. The function $\varrho_{12}(u)$ is given by

$$\varrho_{12}(u) = \frac{\sum_{t=1}^{N} [I_1(t) - \bar{I}_1][I_2(t+u) - \bar{I}_2]}{\left\{\sum_{t=1}^{N} [I_1(t) - \bar{I}_1]^2 \sum_{t=1}^{N} [I_2(t) - \bar{I}_2]^2\right\}^{1/2}}, \tag{1}$$

where N equals the number of longitude points, I_1 and I_2 are the intensities in counts from the two spectroheliograms with mean values denoted by bars, t is the longitude index, and u is the lag index. Examples of the function ϱ are shown in Figure 1.

The cross-correlation function for each latitude and each pair of spectroheliograms was searched for a positive maximum over a range of lags corresponding to sidereal rotation rates between 9.5 and 15.4 deg day^{-1}. The lag corresponding to the maximum was then taken to define the rotation rate in the given line or continuum. Rates thus determined from many pairs of spectroheliograms were averaged together to yield the results presented in the next section.

3. Results

The sidereal rotational velocities for each of the lines and the Lyman continuum are shown in Figures 2 and 3 as a function of solar latitude. As is apparent from these figures, we detect a differential rotation, that is, a variation of the rotation rate with solar latitude, in the emission from the Lyman continuum, O IV, O VI, and Ne VIII. In Table I, we give the parameters a and b of least-squares fits of the function

$$\omega_{\text{sidereal}} = a + b \sin^2 B \tag{2}$$

TABLE I

Data and results of the analysis

Line	λ (Å)	T_{max} (K)	Number of pairs	a (deg day^{-1})	b (deg day^{-1})	σ_{rms}
Ly cont.	800	8.0×10^3	25	13.64	−2.65	±0.46
Ly cont.	[a]	8.0×10^3	81	13.59	−2.34	±0.40
O IV	790	1.8×10^5	24	13.46	−2.98	±0.49
O VI	1032	3.2×10^5	36	13.11	−3.55	±0.44
Ne VIII	770	7.1×10^5	29	13.53	−3.43	±0.40
Average	–	–	–	13.46	−2.99	±0.44
Mg X	625	1.4×10^6	71	13.31[b]	–	±0.66
Si XII	499	2.2×10^6	58	13.13[b]	–	±0.54
Fe XVI	361	3.5×10^6	60	12.58[b]	–	±0.63

[a] The spectroheliograms used were centered on 6 wavelengths in the Lyman continuum: 897, 865, 826, 800, 740, 667 Å.

[b] These quantities represent average values of the rotation rate taken over all latitudes.

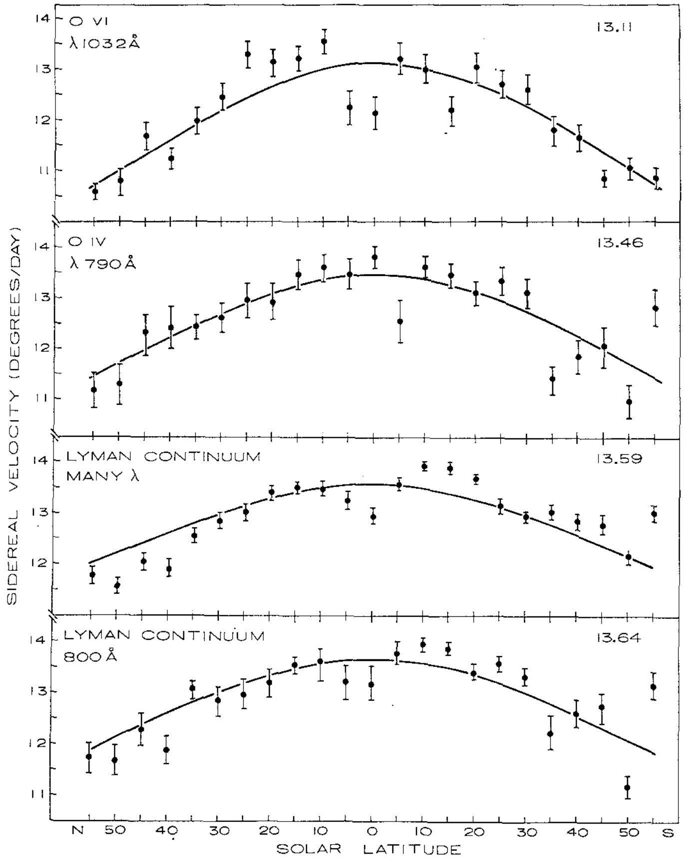

Fig. 2. The rotational velocity as a function of solar latitude B. The error bars at each latitude represent the standard deviation of the average of the rates determined for each spectroheliogram pair. The solid line is the least-squares fit to the data and the sidereal equatorial velocity (deg day^{-1}) is indicated in the upper right corner of each section.

to the data for the Lyman continuum, O IV, O VI, and Ne VIII. Here B is the solar latitude. Because no significant variation of a and b is apparent, we averaged these coefficients to obtain an average differential rotation rate (deg day^{-1}) in the chromosphere and transition region of

$$\omega_{\text{sidereal}} = 13.46 - 2.99 \sin^2 B \,. \tag{3}$$

The results for Mg X, Si XII, and Fe XVI do not show as clear evidence for differential rotation. When a least-squares fit of the form of Equation (2) is applied to the rotation rates for Mg X, Si XII, and Fe XVI, the parameter $|b|$ turns out to be less than for the other features, and the rms deviation of the fit is comparable to that for a straight average. Hence, solid body rotation ($\omega_{\text{sidereal}} = \text{constant}$) would be as satisfactory a representation of the data as a differential rotation curve. For these ions we give in Table I simply the rates averaged over latitude. We also include in Table I for each

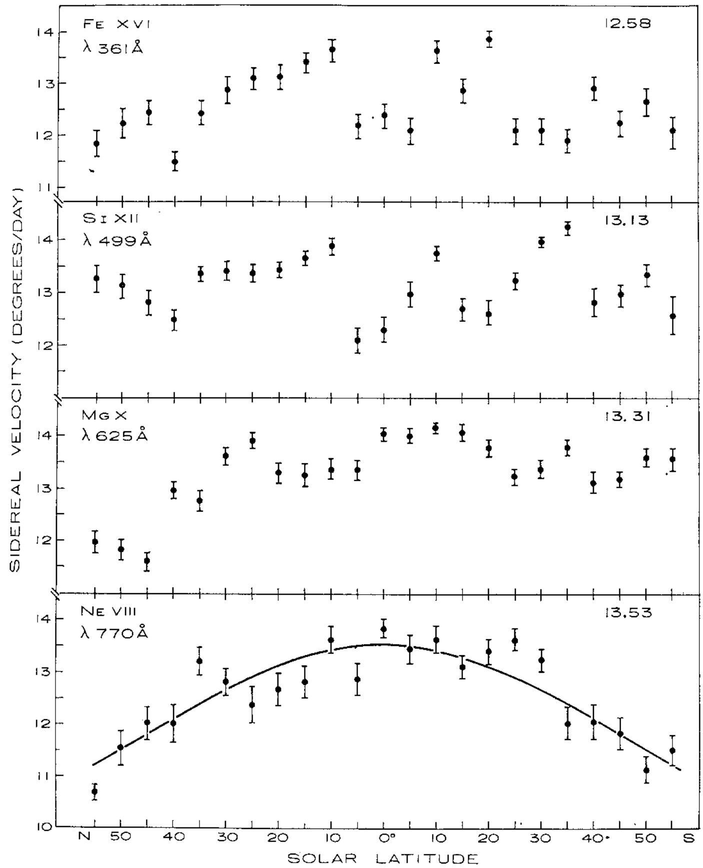

Fig. 3. The rotational velocity as a function of solar latitude *B*. The solid curve is the least squares fit to the Ne VIII data. In the upper right corner, the equatorial velocity (deg day^{-1}) is indicated for Ne VIII; the velocity averaged over all latitudes is given for Mg X, Si XII, and Fe XVI.

spectral feature the 'temperature of formation' defined by the maximum rate of emission per electron for each ion, the number of pairs of spectroheliograms used for each determination, and the rms deviation of the observed rates from the least-squares fits to Equation (2) or from the averaged value. A similar analysis using spectroheliograms separated by one solar rotation (~27 days) rather than only a few days yielded rotation rates that agreed within the errors with the rates in Table I and showed no systematic effects.

The values of the equatorial velocity (equal to the *a* parameter in Table I) show no significant dependence upon the temperature of formation in the atmosphere. However, our ability to detect a height-variation in the rotation rate may be lessened by the fact that all of the emission lines, with the exception of Mg X and Fe XVI lie on various background continua (Dupree and Reeves, 1971). The continua have not been removed from the spectroheliograms in the Atlas (Reeves and Parkinson, 1970) and thus contribute to the measured line intensity in the 3.2 Å bandpass of the OSO-4 experiment. The relative contribution of a continuum depends upon the transition. In the quiet Sun, the carbon recombination continuum contributes only 4% to the measured O VI intensity; the Si XII line lies on the helium continuum, which contributes 40% to its measured quiet-Sun intensity. In active regions, the continua make relatively smaller contributions to the total measured intensities because they are enhanced less than the superposed lines that are formed at higher temperatures. In any case, data that combine measurements of emission formed at different temperatures, and by implication at different heights, may obscure a variation of the rotation rate with height.

4. Comparison with Other Results

Figure 4 shows a comparison of determinations of the sidereal rotation rate by different methods. The curve formed by short broken lines is taken from Newton and Nunn's (1951) measurements of long-lived sunspots. The remaining curves are other determinations from data obtained during the same year or quarter of a year as our observations. The long broken lines represent results of spectroscopic observations on the disk of line shifts of the photospheric Fe I line at 5250 Å during the last quarter

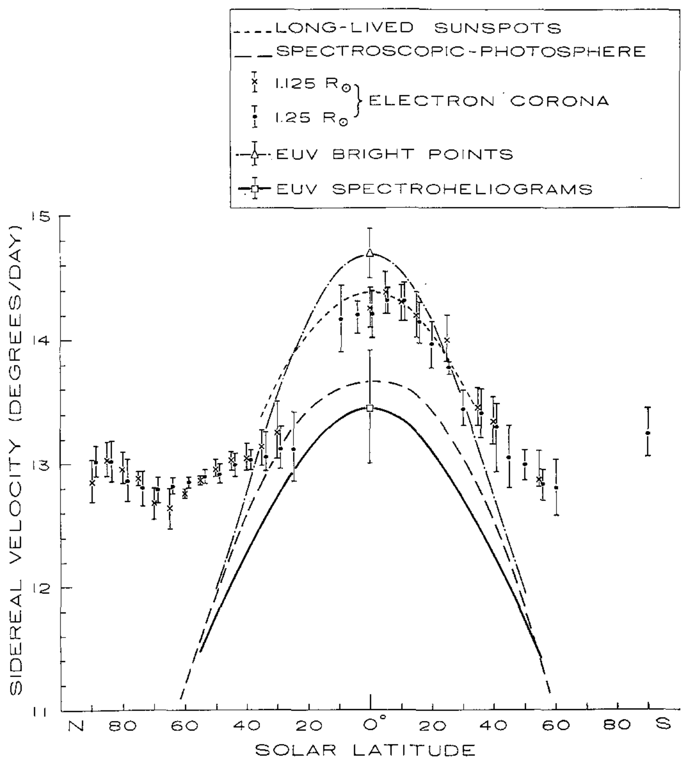

Fig. 4. Comparison of different determinations of the solar differential rotation. The open square and intersecting solid curve denote the results of this paper (EUV spectroheliograms). See text for references and discussion.

of 1967 (Howard and Harvey, 1970). The crosses and filled circles indicate values derived from observations of recurrent limb features at two heights in the white light corona during 1967 (Hansen *et al.*, 1969). The open triangle and the intersecting dash-dot line mark the equatorial rotation rate and the differential rotation as determined by the apparent displacement of the brightest points in active regions on Mg X spectroheliograms from OSO-4 (Simon and Noyes, 1972). The spectroheliograms are a subset of those employed in this investigation. The averaged differential rotation rate found in this paper is indicated by the open square and intersecting solid line (EUV spectroheliograms).

Our determination of differential rotation in the chromosphere and transition region agrees well with the spectroscopically-derived rotation rate (Howard and Harvey, 1970). However, both of these rates are slower at the equator by ~ 1 deg day^{-1} than the equatorial rotation rate determined by tracers on the disk (sunspots, EUV bright points) or at the limb (recurrent features in the white light corona).

5. Discussion

The rotation rates observed in the 'coronal' lines Mg X, Si XII, and Fe XVI do not display differential rotation as clearly as do the other features. Low count levels in the OSO-4 instrument may introduce greater uncertainty in the Fe XVI results but not in Mg X and Si XII. However other observations also show departures from simple differential rotation in the solar atmosphere. Solid body rotation in equatorial regions ($B \lesssim 30°$) has been noted in the photospheric magnetic field and Fraunhofer lines (Livingston, 1969a; Wilcox and Howard, 1970). At high latitudes, departures from simple differential rotation can be seen in the K-coronameter measurements (Figure 4). Our results support departures from a rotation law as given by Equation (2) and suggest that differential rotation is not as pronounced in the corona as in the underlying layers of the atmosphere.

A matter of concern to us is the discrepancy between our differential rotation rates and those of Simon and Noyes (1972). The two rates were obtained from the same EUV spectroheliograms but were derived independently by different methods. One possible explanation is an incorrect theoretical technique or computer program. However, artificially constructed spectroheliograms and cross-correlation functions yielded correct results.

A more probable explanation of the discrepancies shown in Figure 4 may be the inherent differences in the lifetime and associated magnetic-field strength among the features that are used to measure the solar rotation (Wilcox, 1972). The fast (~ 14.5 deg day^{-1}) equatorial rate is found from long-lived features that correspond to strong magnetic field regions. Sunspots are well-known examples. Also, study of EUV spectroheliograms has demonstrated (Noyes and Withbroe, 1972) the correlation between high line intensity (i.e., active regions) and increased (photospheric) magnetic field. The K-coronameter results (Hansen *et al.*, 1969) are similar to the sunspot measurements in that they are derived from recurrent features with lifetimes greater than one solar rotation. White light coronal features also map the magnetic field configurations in the corona (Newkirk, 1971). Autocorrelation analyses of magnetograms themselves (Wilcox and Howard, 1970) confirm the agreement between the rotation of the photospheric magnetic field and recurrent sunspots at the equator and K-coronameter observations at higher latitudes. In contrast to these observations that map the magnetic fields, the spectroscopic measurements of Howard and Harvey (1970) record the motion of the solar plasma during a short time period ($\sim$90 min) irrespective of the magnetic field strength.

Because we have used full disk spectroheliograms and statistical techniques, the measurements in this paper do not clearly represent any of these features. A cross-correlation function, as given by Equation (1), weights the deviations from an average value. Maxima in the cross-correlation function are influenced by regions of lower than average intensity (such as coronal holes) as well as by the points with brighter than average intensity. Although we analyzed the same data, our results are not comparable then with those of Simon and Noyes (1972). The brightest point in each of a few active regions such as they considered would not contribute significantly to our cross-correlation analysis involving the usable portions of the spectroheliogram ($\sim$600 points). Additional confirmation that our results are not biased toward active regions is the consistency of the rotation rates between latitudes where active regions exist, and those latitudes where no active regions are present. This analysis appears to be representative of short-lived emission (because the observational data were taken over $\lesssim$3 days), corresponding to both active and quiet features. Hence, it is reasonable to find that rotation rates agree closely with those from spectroscopic measurements.

The equatorial rotation rate of 13.46 ± 0.44 deg day^{-1} that we derive appears to provide the first evidence that the solar plasma in the chromosphere, transition region, and corona rotates at the same rate as the photospheric plasma. These results support the suggestion (Wilcox, 1972) that the photospheric and solar wind plasma rotate more slowly than the magnetic field patterns.

A further investigation, made with similar techniques, is to be carried out (Henze and Dupree., 1973) with the spectroheliograms acquired by the Harvard College Observatory experiment on OSO-6. These observations have the advantage of better spatial resolution, and a time-base spanning many solar rotations.

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