SOLAR ROTATION AS MEASURED IN EUV CHROMOSPHERIC AND CORONAL LINES

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Abstract. Active regions were followed across the disk on OSO 4 spectroheliograms in the Lyman continuum (LC) and in Mg x λ625. These observations indicate differential rotation with latitude, but not with height in the atmosphere. The measured equatorial sidereal rotation velocity is 14.7° ±0.2° per day in both chromospheric LC and coronal Mg x, where the quoted error is the standard deviation of a least-squares fit to the data.

1. Introduction

Numerous studies have been made of the solar differential rotation. These have been both of the spectroscopic type (see, e.g., Howard and Harvey, 1970) and of the tracer method, in which transit times of individual features, such as sunspots or prominences, are measured (e.g., Newton and Nunn, 1951). In addition, Wilcox and Howard (1970) and Wilcox *et al.* (1970) have used autocorrelation studies of synoptic charts of the photospheric magnetic field to measure rotation of magnetic fields, both in active regions and in the background field. Almost all the previous work has measured either photospheric or chromospheric velocities, the upper height limit being set by the heights of formation of Hα and Ca^+K, in which most chromospheric studies have been made. Only a few attempts have been made to measure the differential rotation at higher elevations, using, for example, K-coronameter data (Hansen *et al.*, 1969) or limb observations in Hα prominences or in the coronal green line (e.g., Trellis, 1957), but these have been inherently inaccurate, since the time resolution is so poor (13 days between observations) that the likelihood of observed features remaining spatially fixed between observations is very small. In addition, Ward (1966) has pointed out that such long-lived features tend to rotate slower than smaller, short-lived features; thus, the velocity data are biased to the low side if features are measured only at successive limb passages.

In this investigation, using EUV spectroheliograms taken by the Harvard experiment on the OSO 4 satellite, we have been able for the first time to make observations of active regions in coronal lines many times during their passage across the disk. Further, observations were made of active regions both in the chromosphere (using the LC) and in the low corona (with Mg X 625 and Si XII 499). Therefore, it was also possible to search for height variation of the differential rotation, since these coronal lines are formed about 10000 km higher in the atmosphere than is the LC (Simon and Noyes, 1972; hereafter referred to as Paper I).

Some of these results have been previously presented in preliminary form (Simon and Noyes, 1971; Simon, 1972).

2. Observations

Most of the observational details have been described in Paper I and will not be repeated here. In brief, the method was to measure the heliographic latitude and longitude of the brightest points (local intensity maxima) in each active region, and then to follow these points across the disk until they disappeared. We used the criterion that a point was considered to have disappeared if it had not been observed at least once in the previous 1300 min (13 orbits of the satellite). A point could disappear for two reasons: either it might become dimmer and cease to be a local brightness maximum, or it could undergo a sufficiently large proper motion (defined as greater than 40″ from the position expected from extrapolating previous locations) so that the computerized data-reduction program no longer recognized it as the same point, but tallied it instead as a new one.

Usable spectroheliograms for this experiment were obtained between orbits 130 and 627 of the OSO 4 satellite, between 27 October and 29 November, 1967. Mg X spectroheliograms were acquired in 83 orbits, Si XII in 32, and LC in 31. From these, we were able to follow the rotation paths of 55 bright points in Mg X and 44 in LC.

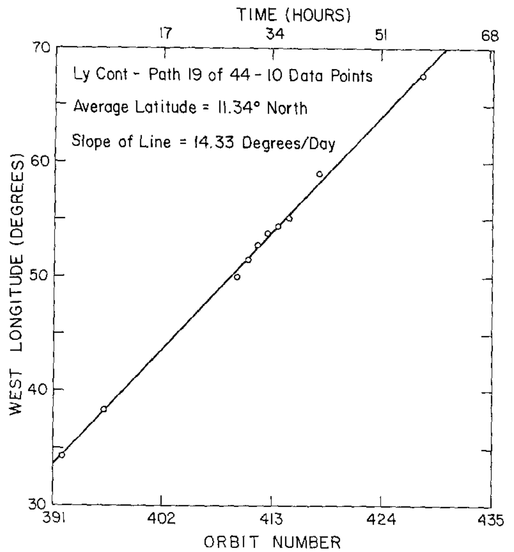

Fig. 1. Typical path of a bright active region point, seen in the Lyman continuum. The point was observed in 10 different orbits of the spacecraft, over a total time of 56 h. The least-squares straight-line fit to the data gives a sidereal longitudinal velocity of 14.33°/day.

The Si XII data yielded paths for 27 bright points. However, these data are much less reliable than the Mg X or LC data, owing to the low instrument efficiency at 500 Å and to possible contamination of the data by the underlying He I continuum. We therefore do not include them in the analysis.

A typical rotation path in LC is shown in Figure 1. The angular velocity ω for each bright point was found from a least-squares fit of the form $\phi = \omega t + \phi_0$, where ϕ is the heliographic longitude; all data points were weighted equally in this fit. Several bright points were observed on more than 30 orbits, while the longest path length extended over a time interval of more than 5 days. The observations were restricted, of course, to those latitudes containing active regions, which meant at the time of OSO 4 between 8° and 30°, with an additional 4 points between 40° and 50°.

3. Results

The data were fitted by least-squares to a curve

$$\omega = a + b \sin^2 \theta, \tag{1}$$

where a and b are sidereal velocity in deg/day, and θ is the heliographic latitude. The results are illustrated graphically in Figures 2 and 3. Note first in Figure 2 that the velocity in LC (solid line) agrees very closely with Newton and Nunn's sunspot observations ($\omega = 14.4–2.8 \sin^2 \theta$), which are shown as x's. The separation of the two curves is well within the 95% confidence band (dashed lines), which measures the

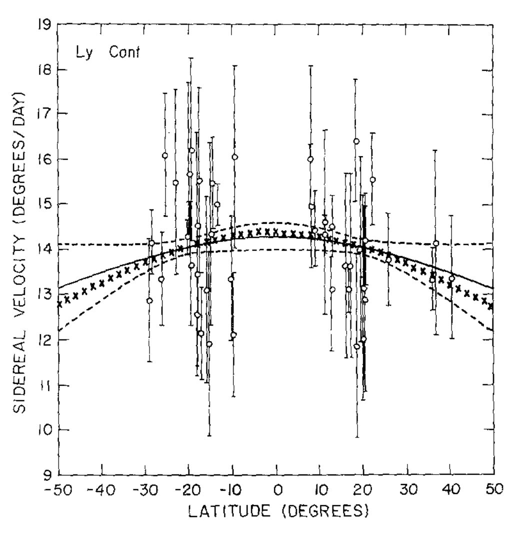

Fig. 2. Sidereal rotational velocity measured in the Lyman continuum. The solid line is a least-squares fit $\omega = 14.29–1.94 \sin^2\theta$, where ω is in deg/day, and θ is the heliographic latitude. The dashed error band delineates the 95% confidence limit on the fitted function. The lengths of the error bars on the data points are inversely proportional to the number of observations that produced the points. Newton and Nunn's (1951) sunspot observations are shown as x's.

statistical reliability of the solid line fit (Deming, 1943). The narrowness of this band might appear to be inconsistent with the large scatter in the data points. However, the width of the confidence band is analogous to the standard deviation in the mean (σ_m), not the sample standard deviation ($\sigma \approx \sqrt{N}\,\sigma_m$, where N = number of observations). One would expect 95% of the data points to lie within $\pm 2\,\sigma$ of the curve, but only a much smaller number to lie within $\pm 2\,\sigma_m$. The meaning of a 95% confidence band is that other sets of observations, fitted to Equation (1), will produce curves that fall within this band 95% of the time. The lengths of the error bars on the individual data points are inversely proportional to the number of observations (i.e., the number of orbits in which the bright point was seen) that produced that result, and are normalized such that the average length of the bars is 2 σ.

In the case of Mg X, illustrated in Figure 3, the velocity structure looks quite

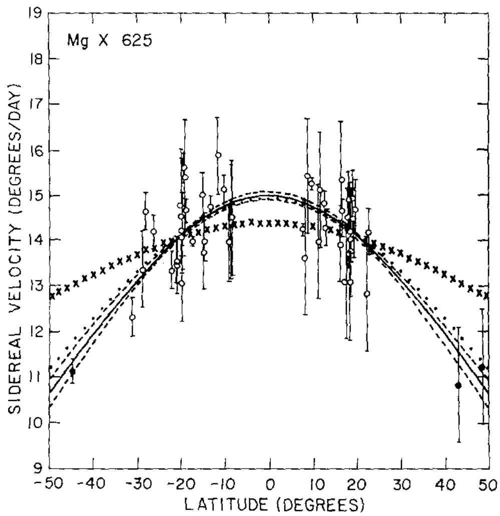

Fig. 3. As in Figure 2, for Mg X 625, with $\omega = 14.99–7.42 \sin^2\theta$. The dotted line is a second fit, not using the three data points (filled circles) at 43°, 45°, and 49° latitude; this second fit ($\omega = 14.90–6.36 \sin^2\theta$) was to determine if the large latitudinal variation was due primarily to these three high latitude points. It can be seen that these points steepened the curve slightly, but the relative shift was within the confidence band for latitudes up to 24°.

different from that of LC, being higher at low latitudes and smaller at the higher ones. Comparing this figure with Figure 2, it would appear that the equatorial velocity in coronal Mg X is approximately 5% higher than in chromospheric LC or in sunspots, which lie 10000–12000 km lower in the atmosphere. However, this is not the case, because corrections must be made for the effect of a significant difference in limb brightening of the optically thin Mg X line (Withbroe, 1970a, b) and the optically thick LC (Noyes and Kalkofen, 1970). We have explained in Paper I that the apparent position of a bright point will be shifted slightly limbward in a limb-brightened line and centerward in a limb-darkened one. Hence, our measured rotational velocities will be too high in a limb-brightened line and too low in one that shows limb darkening.

To estimate the size of this effect, we computed the equatorial velocity a (Equation (1)) first by including all the data points (these had radius vectors $\varrho \leqslant 0.92$). These calculations led to Figures 2 and 3. Then we used only points with $\varrho \leqslant 0.90$, 0.88, etc. and in each case recomputed the equatorial velocity. As ϱ becomes smaller, the effect of limb brightening should become less, and a plot of a vs. ϱ should approach asymptotically a constant as $\varrho \to 0$. Unfortunately, as ϱ becomes smaller, the data available for the analysis become fewer, and the statistics, poorer, so that we were unable to compute a for $\varrho < 0.4$. The results are given in Figure 4a and show the expected behavior for LC and Mg x. The smooth curves are parabolas of the form $a = a_0 + a_1 \varrho^2$, which have zero slope when $\varrho = 0$. We see that the LC value $a = 14.3°$/day at $\varrho = 0.92$ (see Figure 2) increase to $a = 14.7$ when $\varrho = 0$, while the Mg x value $a = 15.0$ at $\varrho = 0.92$ (Figure 3) is reduced to $a = 14.7$ when $\varrho = 0$. These quoted values have a standard deviation σ_a between 0.1° and 0.2°/day.

The effect of limb brightening on the coefficient b of Equation (1) was computed in a manner similar to that described above. The results are shown in Figure 4b. It is clear that the data are not good enough to determine this parameter with much

b

a

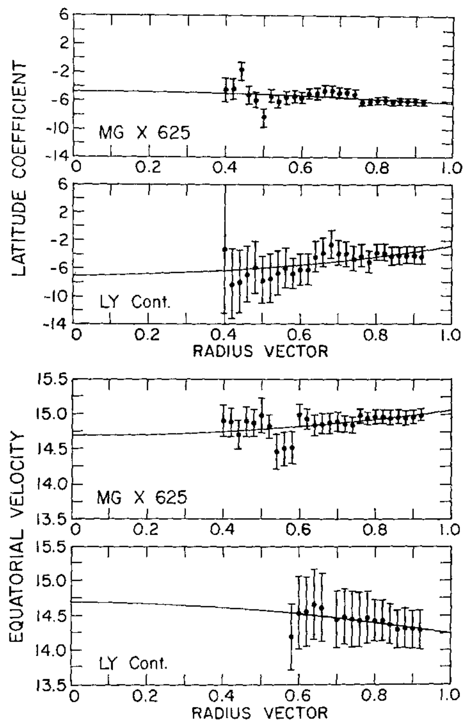

Fig. 4. (a) Dependence of the equatorial velocity (in deg/day) on limb brightening. Each circle represents a calculation made with a slightly different set of data. The restriction was that no data point in a set could have a radius vector greater than the abscissa value of the corresponding circle. Thus circles at larger radius vectors were obtained using larger sets of data; hence their smaller error bars (each bar extends $\pm 2\,\sigma$). (b) Dependence of the latitudinal component of the rotational velocity (in deg/day) on limb brightening.

precision, the standard deviations σ_b of the fitted curves being some 5–10 times larger than σ_a for the equatorial velocity parameter.

In Table I we summarize our results, together with the sunspot velocities of Newton

TABLE I

Solar sidereal rotation velocity

Observation	a	σ_a	b	σ_b	σ	σ_m	N	Height of formation (km)	ω_{lat}	$2\sigma_\omega$
LC	14.7	0.2	−7.1	1.1	1.1	0.2	44	2000	−0.03	0.32
Mg X	14.7	0.1	−4.7	0.9	0.6	0.1	55	11000	0.07	0.07
Newton and Nunn	14.4	0.01	−2.8	0.08	–	–	715	0	–	–

and Nunn. The quantity σ is the sample standard deviation, σ_m the standard deviation in the mean, σ_a and σ_b the standard deviations of a and b, respectively, and N the number of observations. The tabulated values of the velocity components a and b refer to the extrapolated values at $\varrho=0$ obtained from Figures 4a and b. The heights of formation are taken from Paper I.

In Table I we also list the value ω_{lat}, the average latitudinal velocity, in degrees per day. One expects this quantity to be close to zero. In both cases, the latitudinal velocity deviates from zero less than σ_m measured for the longitudinal velocity and also less than $2\sigma_\omega$ (last column in Table I), which gives the 95% confidence limit on the measured value of ω_{lat}. Thus, to the accuracy of our observations, the latitudinal velocity is essentially zero, which gives us some confidence in the reliability of our statistics.

4. Discussion

These EUV observations are of interest because they provide the first continuous observations of small coronal features as they cross the disk and thus yield more accurate rotational velocities than can be obtained by coronagraphic observations made at the limb.

The main result of this study is the apparent constancy of the solar rotational velocity with height between chromosphere and low corona. This is in excellent agreement with earlier works using tracer techniques (chromospheric structures (D'Azambuja and D'Azambuja, 1948), sunspots (Newton and Nunn, 1951), and coronal limb features (Trellis, 1957; Hansen *et al.*, 1969; etc.)), all of which are associated with active regions and thus with an underlying magnetic field structure, and which have consistently yielded velocities close to photospheric spectroscopic values.

However, several points with regard to our observations need to be clarified. Because all the observations were obtained in one 33-day period in 1967, we are unable to say how applicable our results are to other times, since it is well known (Howard and Harvey, 1970) that there exist not only daily fluctuations (typically 3–4%) in the solar rotation velocity, but also longterm secular variations. Further, essentially all our measurements were made at latitudes between 10° and 30°, so that our primary result, the equatorial velocity, is of necessity an extrapolated value, as is the velocity at high latitudes. Finally, the reader will have noticed that the scatter in our data is large; for Mg X and LC, respectively, values of σ are 0.6° and 1.1°/day, or 4 and 8%, and our sample is small, consisting only of 55 and 44 observations.

For all the above reasons, we emphasize the tentative nature of these results. It will be of interest to see if the more recent OSO 6 satellite observations, with better spatial resolution and a much longer lifetime (almost 1 yr), will confirm the present work.

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