GREEN CORONA AND SOLAR SECTOR STRUCTURE

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Abstract. Analysis of the green line corona for the interval 1947–1970 suggests the existence of large-scale organization of the emission. The green line emission at high northern latitudes ($\approx 40°$–$60°$) is correlated with the emission at high southern latitudes 6, 15 and 24 days later, while the low latitude green corona seems to be correlated on both sides of the equator with no time lag. These coronal features are recurrent with a 27-day period at all latitudes between ± 60°, and we associate these large-scale structures with the solar magnetic sector structure. The high correlation between northern and southern high-latitude emission at 15 days time lag is explained as a signature of a two-sector structure, while four sectors are associated with the 6 and 24 day peaks.

The green line (Fe XIV 5303 Å) corona has been observed regularly on a synoptic schedule for about a quarter of a century. Sýkora (1971; personal communication, 1973) has prepared synoptic tables of the intensity on the Pic-du-Midi photometric scale of the green corona for the interval 1947–1970. The observations are referred to central meridian by averaging the intensities measured at the limbs seven days before and seven days later and one value is computed per day for six latitude zones: high latitudes (57°.5N–37°.5N and 37°.5S–57°.5S), middle latitudes (37°.5N–17°.5N and 17°.5S–37°.5S), and low latitudes (17°.5N–2°.5S and 2°.5N–17°.5S). The daily values were then condensed into three-day averages resulting in nine such average intensity figures per solar rotation. In a series of papers we have investigated some properties of large scale features of the green corona using daily values of the intensity interpolated from Sýkora's tables. It is clear that the resulting data sets have been extensively smoothed; we consider this to be an advantage for the study of large-scale and long-lived structures. Very long period variations – such as the 11 yr sunspot cycle – have been removed by subtracting a running 27-day mean from the data.

In Antonucci and Svalgaard (1974) we showed that the green corona has both differential and rigid rotation. Short-lived features (symptoms of solar activity) rotate with the same rate as magnetic fields in the underlying photosphere showing considerable differential rotation with latitude. Long-lived structures rotate rigidly for the entire latitude interval from 57°.5N to 57°.5S with a synodic period slightly larger than 27 days. This rotation period is an average over the interval 1947–1970. A two-component corona was suggested. One component rotates with the rotation rate characteristic of short-lived magnetic fields in the photosphere – having a considerable degree of differential rotation – and is probably directly related to active regions. The other component seems to rotate rigidly with a period independent of latitude up to at least ≈ 55°. We could associate this rigidly rotating component with emission from plasma

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trapped on closed field lines across rigidly rotating solar magnetic sector boundaries (Wilcox and Howard, 1968; Wilcox and Svalgaard, 1974).

That a relationship between the intensity of the coronal green line and the solar sector boundaries exists was shown by Antonucci (1974), Svalgaard *et al.* (1974a) and Gulbrandsen (1973a, b). Gulbrandsen (1973b) suggests that the green line coronal configuration associated with a sector boundary consists of a narrow enhancement at the sector boundary and a low emission region several days wide to the east of it. As pointed out by Wilcox and Svalgaard (1974), the region near the solar sector boundary appears to have closed magnetic field lines which might tend to inhibit the outward expansion of the corona. A few tens of degrees of longitude (a few days of solar rotation) away from the boundary there appear to be regions with open coronal field lines indicating escaping solar wind plasma and reduced coronal density and emission. The coronal hole observed by Krieger *et al.* (1973) was in fact located two or three days eastward of a solar sector boundary.

Antonucci (1974) found that enhancements of the green corona show an organized pattern within solar magnetic sectors. The emission maxima are closely related to sector boundaries in the way that during a given sunspot cycle coronal enhancements at middle and high latitudes are found to be close to sector boundaries with one polarity change, (say: away → toward) in the northern hemisphere but close to the sector boundary with the opposite polarity charge (here: toward → away) in the southern hemisphere. This relationship changes near sunspot minimum.

A concise statement of her finding is that sector boundaries separating leading and following polarities show more green coronal emission at middle and high latitudes than the other kind of boundary. For average sectors ≈ 7 days wide there is therefore a tendency for enhanced coronal emission in regions in opposite hemispheres at rather high latitudes and separated by $\approx 90°$ in longitude. In the above discussion it has been assumed that solar sector boundaries are generally oriented north-south on the Sun as suggested by comparisons between the interplanetary field in the ecliptic with the photospheric magnetic field (Schatten *et al.*, 1969). If we consider the sector boundary in a more strict sense as just providing a precise time marker when it is observed in the ecliptic the result of Antonucci (1974) suggests that persistent middle and high latitude coronal features are present in each hemisphere but displaced in heliolongitude by 90° or more depending on the width of solar magnetic sectors.

This suggestion can be tested without explicit reference to solar sectors because a considerable correlation should exist between the green line intensity observed at high northern and at high southern latitudes respectively. We have calculated cross correlation functions between corresponding northern and southern latitude zones of the green line intensity data for the high, middle and low latitude zones with time lags varying from -90 to $+90$ days. The result is shown in Figure 1. For each latitude zone there are correlation peaks with amplitudes in excess of 0.1. The very fact that *any* correlation exists between corresponding latitude zones in opposite hemispheres at a lag significantly different from zero for these 24 yr long time series, strongly suggests that the green line corona includes a component which is organized on a very large scale. The

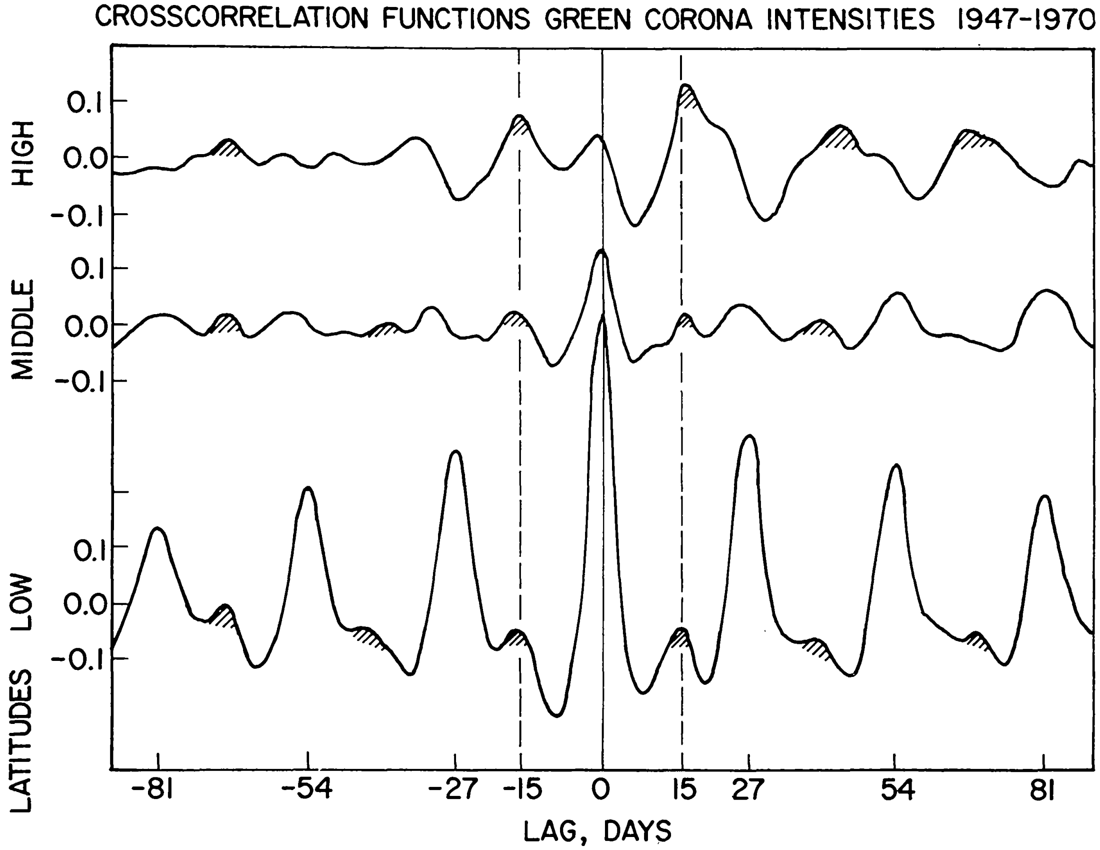

Fig. 1. Cross-correlation functions for intensity of the green line corona during the interval 1947–1970 with a time lag varying from −90 to +90 days. The upper curve shows the cross-correlation between high northern latitudes (47°5N) and high southern latitudes (47°5S). The middle curve shows the correlation between latitude zones 27°5N and 27°5S, and the bottom curve shows the correlation between latitude zones 7°5N and 7°5S. The latitude zones are 20° wide and are centered on the latitude values given above.

peak at zero lag for the high latitude zones does not show any 27-day recurrence and is presumably due to random noise which is common to both latitude zones, such as varying sky transparency, change of observatory from which the reported green line emission was derived by Sýkora, etc. A noise contribution of the same size as this peak should then be contributing to the other zero-lag peaks too.

Let us first discuss the cross-correlation function for the low latitude zones. There is a pronounced 27-day recurrence which we interpret as the synodic rotation period for the low latitude corona. Secondary peaks (shaded in Figure 1) are present and these are also recurring with the 27-day period. The principal peaks occur, however, at lags 0, ±27, ±54, etc., indicating that the coronal emission at low latitudes (17°5N–17°5S) occurs predominantly at the same longitude. The secondary peak, displaced by 15 days (200° in longitude), suggests the presence of coronal enhancements structured in two low-latitude regions approximately opposite in longitude. This is in agreement with a previous study of the relation between *low*-latitude green line corona and the solar sector structure (Antonucci, 1974) which showed that equatorial coronal emis- occured preferentially near (toward-away) sector boundaries during sunspot cycles 18 and 20 and near (away-toward) boundaries during cycle 19. If we combine this with the fact that often either 2 or 4 sectors are seen, the correlation discussed above can be understood.

It is interesting to note that the overall correlation between middle latitude zones is poorer than between either corresponding low or high latitude zones. The correlation curve looks like a blend – but with much reduced amplitude – of the low and the high latitude curves. We assume that this is the case and that in addition the coronal emission over active regions plays a larger role in reducing the correlation between opposite hemispheres for these middle latitudes (17°.5–37°.5).

The cross-correlation between the two high-latitude zones (Figure 1, top curve) has its highest peak value (+0.14) at a lag of +15 days. This means that 15 days (200°) after the appearance of a green line enhancement at high northern (47°.5N) latitude an enhancement is observed at high southern latitudes. Other significant peaks are seen at 15+27 and 15+ (2×27) days indicating that the enhancements are long-lived and rigidly rotating. We suggest that these features are associated with sector boundaries on the Sun.

The shape of the correlation peaks suggest the presence of a non-resolved fine structure. The peaks are very wide and have shoulders. To resolve this fine structure, the long-term variations have been removed from the coronal data by subtracting a running mean over 27 days, 15 days and 7 days respectively. This successively sharpens the peaks corresponding to short period variations as can be seen in Figure 2. The dashed vertical lines identify secondary peaks 6 and 9 days from the principal peaks which are shaded. Stated differently, there are structures which are correlated with time lags of ±9 days and ±24 days ($9=15-6$; $24=15+9$). We are led to the conclusion that some coronal high-latitude features in the north are followed by southern features shifted by 120° (9-day peak) and by 320° (24-day peak) in longitude.

We can also completely filter out the secondary peaks by computing a 12 day running average of the intensity and subjecting these very smoothed time series to the cross correlation analysis. The result is seen in Figure 3 where only the peaks corresponding to the 15 day lag are present for the cross correlation between high northern and high southern latitudes (top curve). We conclude that certain coronal high-latitude features in the north are followed by southern features shifted by 200° (15-days) in longitude.

The solar sector structure most often has four or two sectors – maybe depending on the phase of the sunspot cycle (Svalgaard, 1972). If we assume that a two-sector structure is associated with coronal enhancements in opposite hemispheres, one in the north and another in the south displaced by about 180° in longitude, we would expect that high emission at about 45° north should be followed by high emission at about 45° south after a delay of about 14 days. For four sectors we may assume (Antonucci, 1974) that high emission at 45° north should be followed by high emission at 45° south displaced 90° in longitude or 7 days. Furthermore there should be two northern and two southern enhancements, each pair having a separation in longitude of 180°, so that high emission at 45° north is also followed by high emission at 45° south after

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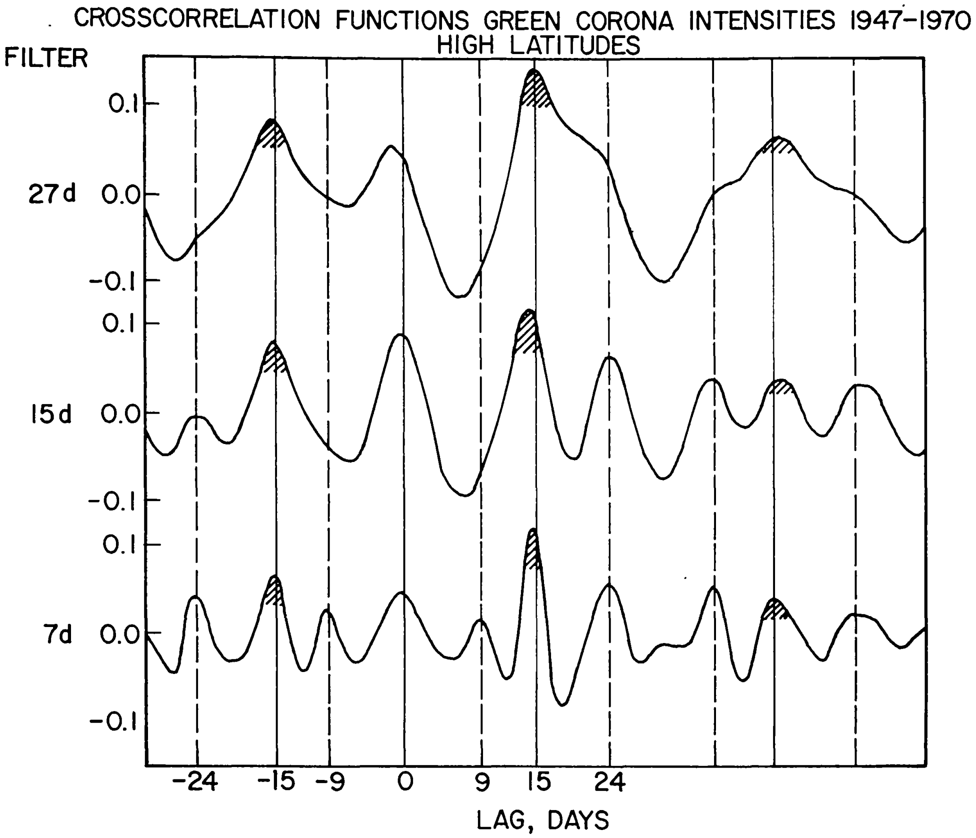

Fig. 2. Cross-correlation functions of green line corona for the interval 1947–1970. The emission in the high latitude zone (57°.5N–37°.5N) is cross-correlated with the emission in the zone (37°.5S–57°5S) for lags varying from −30 to +60 days. Long-term variations have been removed by subtracting a running mean over 27 days for the upper curve, 15 days for the middle curve, and 7 days for the bottom curve. This successively sharpens peaks corresponding to short period variations.

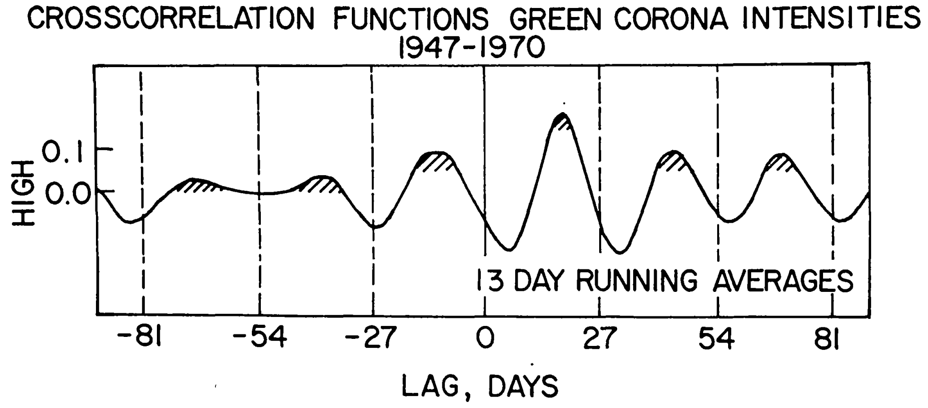

Fig. 3. Cross-correlation functions of 13-day running averages of high-latitude (47°.5) green line corona for the interval 1947–1970.

a delay of $14+7=21$ days. In other words a four-sector structure would result in high correlation between the northern and the southern high latitude zones at time lags of $14-7=7$ and $14+7=21$ days, while a two-sector structure would result in high correlation at a time lag of 14 days.

Indeed as seen in Figure 2 high correlation exists for time lags of $15-6=9$, 15, and

15+9=24 days. These delays, we surmise, are sufficiently close to the 14−7=7, 14, and 14+7=21 days emerging from the above considerations, to suggest that indeed it is the solar sector structure that is organizing the part of the green corona emission coming from plasma condensations trapped along magnetic field lines closing over the sector boundary. This viewpoint is consistent with a recent model of large-scale solar magnetic fields by Svalgaard *et al.* (1974b).

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