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THE HALE SOLAR SECTOR BOUNDARY

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Abstract

A Hale solar sector boundary is defined as the half (northern hemisphere or southern hemisphere) of a sector boundary in which the change of sector magnetic field polarity is the same as the change of polarity from a preceding spot to a following spot. Above a Hale sector boundary the green corona has maximum brightness, while above a non-Hale boundary the green corona has a minimum brightness. The Hale portion of a photospheric sector boundary tends to have maximum magnetic field strength, while the non-Hale portion has minimum field strength.

Solar Physics

The Hale Solar Sector Boundary

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There is growing acceptance of the importance of large-scale structures on the sun. Such large-scale organizations of solar features are being recognized both on spatial and on temporal scales. Solar activity is also being studied with increasingly higher resolution in time and space; the interplay between these small-scale features and the large-scale structures is poorly understood both observationally and theoretically.

The l^rge-scale solar structures can be divided into zonal structures and sectorial structures. Zonal structures include the polar caps (e.g. Howard, 1972), the sunspot zones, and the prominence zones (e.g. Waldmeier, 1973). Sectorial structures include magnetic sectors (e.g. Wilcox, 1968) and at least some coronal holes (Timothy et al., 1975). With each class of structures there are associated phenomena that share basic characteristics of their class. In particular we should mention the varied influences of these large-scale structures on the corona and its entension into the solar wind. The importance of magnetic fields for all classes of structures is paramount.

Due to their antisymmetric character the zonal structures exhibit a strong solar cycle dependence. Magnetic features change polarity with the cycle and the zones move in latitude. The sectorial structures seem to be much less controlled by the solar cycle (Svalgaard and Wilcox, 1975;

Svalgaard et al., 1975), although some coupling has been observed. Magnetic sectors drift slowly westward during the first half of the sunspot cycle and slowly eastward during the second half (Svalgaard and Wilcox, 1975). It is characteristic for sectorial structures to show little or no differential rotation, whereas zonal structures are closely linked to - and possibly maintained by - the differential solar rotation. These rather different properties of the zonal and the sectorial structures are difficult to explain and have lead to the suggestion (Wilcox, 1971) that the two classes of structures have different origin and co-exist more or less independently.

Observations of the sun show the zonal structures most readily, while observations of the interplanetary medium (at least near the solar equatorial plane) show clear sectorial structures which then can be used in statistical analyses to recover sector structure in the photosphere. In the inner corona, where both structures can be directly observed through the influence of associated enhancements, streamers and current sheets, an extremely complicated configuration can result. Only occasionally is the inner coronal structure simple enough to clearly reveal its nature and origin. With increasing distance from the sun the configuration becomes increasingly simpler, and already at about $6R_{\odot}$ the coronal structure is dominated by large-scale sectorial forms (Howard and Koomen, 1974) in the low-latitude region. At higher latitudes the polar cap fields dominate during most of the sunspot cycle, and it is very likely that this dominance extends into the solar wind (e.g. Svalgaard, et al., 1975) so that the sector structure of the interplanetary magnetic field most of the time is confined to a rather thin region near the solar equatorial plane. The implication is that in most of the heliosphere the polar fields determine the polarity of the interplanetary magnetic field. Such a field geometry could have important consequences for the propagation of cosmic rays within the solar system (Svalgaard and Wilcox, 1976). Discussions of the coronal structure that may result from coexistence of the polar fields and of the low-latitude sector fields can be found in Svalgaard et al. (1974a) and in Hansen et al. (1974).

Since the discovery by Wolfer (1897) that solar activity often has a nonuniform distribution with heliographic longitude, the concept of "active latitudes" has been discussed by several workers. Using the synoptic charts of weak fields from the 'Atlas of Solar Magnetic Fields' observed at the Mt. Wilson Observatory, Bumba and Howard (1969) convincingly showed the reality of active longitudes as recurrences in the large-scale photospheric magnetic field distribution. Bumba and Howard (1969) found a strong regularity of magnetic polarity alternations in longitude and a persistence of these features in time. Single-polarity features (called sections by Bumba and Howard), usually resulting from the fusion of the same polarity fields of several active regions, generally extend across the equator. Such sections can often be followed for at least ten rotations, and form rows when the synoptic charts are arranged below each other in time. Several rows may be associated to form streams that may be followed for several years. These streams as well as the individual rows have a synodic rotation period of 27.0 days and show no differential rotation of the overall pattern, while single short-lived features within the rows do partake in the differential rotation. In addition, intensifications of the streams occur that drift in longitude from one stream to the next, etc., corresponding to a synodic rotation period near 28 3/4 days.

It seems clear that the existence of "active longitudes" implies that the distinction between zonal and sectorial structures is not absolute on an observational basis. Zonal structures can have longitudinal or sectorial organization. A major problem is the identification of the "sections" with the sector structure. The sections are generally too small (typically 30° wide) compared to sectors (typically 90° wide or more) and therefore each sector will often encompass several sections of alternating polarity. Clear observations of individual sector boundaries in the photosphere have not yet been made, thus forcing us to a statistical approach that has not so far been able to reveal the detailed solar source of the sectorial structures. Studies by Antonucci and Duvall (1974) and Svalgaard et.al.(1974b) suggest a coupling between the sector structure and solar activity. We shall discuss this coupling or link in greater detail later in the present paper; for the moment we might comment on a possible implication of a coupling between solar activity and solar sector structure. At first sight such a coupling is obvious: The dispersing remnants of active regions form extended - mainly unipolar - magnetic regions on the sun. These large-scale structures map out into the corona and the solar wind resulting in a similar ordering of the interplanetary magnetic field. Schatten et al. (1968) discuss observations of a solar active region that appeared to produce magnetic loops in the interplanetary medium resulting in the formation of a new sector in the interplanetary magnetic field and suggest that "the evolution of sectors from magnetic bipolar regions" may be similar in general to the specific case they studied. That the dispersion of active regions into weak background fields and the subsequent evolution of these extended fields provide a reasonable explanation for the apparent sectorial structures is a point of view commonly found among solar researchers (e.g. Timothy et al., 1975).

The alternative viewpoint is also viable. Here it is assumed that the sector structure of the magnetic field is a fundamental property of the sun and probably other magnetic stars as well. Physical mechanisms that result in sectorial structures have been discussed by several workers including Stix (1974), Suess (1975) and Wolff (1974). The fundamental large-scale magnetic structures couple to general solar activity resulting in active longitudes and long-lived recurrent features.

As a specific example of an interaction between the zonal and sectorial properties of solar magnetism, we discuss the concept of the Hale sector boundary. As shown schematically in Figure 1, the Hale boundary is the half of a sector boundary in which the change of sector field polarity is the same as the change of polarity from a preceeding spot to a following spot. Consider the righthand boundary in Figure 1, which represents a change of sector field polarity from - to +. In the northern hemisphere this change of magnetic polarity is the same as the change from preceeding to following spot polarity, so the northern half of this boundary is the Hale boundary.

We shall first show that above a Hale sector boundary the green corona has maximum brightness, while above a non-Hale boundary the green corona has minimum brightness. Figure 2 shows the observed relative brightness of the northern green corona during sunspot cycles number 18, 19 and 20 as a function of distance from the sector boundary. The ordinate is the quantity 2(N-S)/(N+S), where N represents the brightness of the green corona on the Pic du Midi scale for each day, and S is the same for the southern hemisphere. Computing the relative brightness of the northern hemisphere in this way removes the effect of brightness variations through the sunspot cycle, and of variations in instrumental calibration. The top curves are for a sector boundary with polarity change from + to - and show that the northern half of such a boundary is at a minimum in coronal brightness in cycle 18, a maximum in brightness in cycle 19, and a minimum in brightness in cycle 20. As shown in Figure 1, the northern half of this boundary was not a Hale boundary in cycles 18 and 20 and therefore has a minimum in coronal brightness. The bottom curves of Figure 2 show that for a sector boundary with polarity change from - to + the relative brightness in the northern hemisphere is just the opposite. In particular, as we see from Figure 1, the northern half of this boundary is a Hale boundary in cycles 18 and 20 and has a clear maximum in coronal brightness in these cycles.

We note in Figure 2 that the time interval between maxima (and between minima) is usually approximately 13½ days, showing that four sectors per rotation is the predominant pattern (Svalgaard and Wilcox, 1975).

The maximum in green corona brightness over a Hale boundary and a minimum over a non-Hale boundary are observed at low, middle and high latitudes. The filled dots in Figure 3 show the relative coronal brightness above Hale boundaries during cycles 18, 19 and 20. The open circles show the relative coronal brightness above non-Hale boundaries during these cycles. We see that the effect is to be found in all three ranges of latitude.

Figure 4 shows how rapidly the Hale portion of a sector boundary changes from the northern hemisphere to the southern hemisphere (or vice versa) near the time of sunspot minimum. The ordinate of the top frame in Figure 4 shows the relative coronal brightness in the northern hemisphere above a boundary with polarity change + to -. During sunspot cycle 19 the northern half of the boundary was a Hale boundary. We see that within one year near 1954 the northern half of this boundary changed from having minimum coronal brightness to maximum coronal brightness. The opposite change occured within one year near 1964 when, with the change of spot polarities from one cycle to the next, the northern half of this boundary changed from being a Hale boundary to a non-Hale boundary.

The bottom frame of Figure 4 shows the total brightness of the green corona as a function of time from 1947 to 1970. Note that there is almost no variation in the maximum coronal brightness from one cycle to the next, despite the fact that the maximum sunspot number decreased by almost a factor of 2 between the maximum of cycle 19 and the maximum of cycle 20. This suggests that the large-scale coronal brightness may be more closely related to the sectorial aspects of solar magnetism (which appear to be relatively unchanging from one cycle to the next) then to the zonal (activity) aspects of solar magnetism.

The Hale portion of a photospheric sector boundary tends to have maximum magnetic field strength while the non-Hale portion has minimum field strength. Figure 5 shows an average synoptic map of the magnitude of the photospheric magnetic field observed at Mt. Wilson Observatory during 1967 to 1973 around 104 sector boundaries in which the polarity changed from - to +. At this time the northern hemisphere portion of this boundary was the Hale boundary, and we see in Figure 5 a maximum in the magnitude of the photospheric field near the boundary in the northern hemisphere and a minimum near the boundary in the southern (non-Hale) hemisphere. Figure 6 shows the same analysis except for 107 sector boundaries with polarity change from + to -. The Hale portion of this boundary at this time was in the southern hemisphere. We see a maximum in photospheric field magnitude near the boundary in the southern hemisphere, and a minimum near the boundary in the northern hemisphere. Thus we see that both the coronal brightness and the magnitude of the photospheric magnetic field are a maximum near the Hale portion of sector boundaries, and a minimum near the non-Hale portion of boundaries.

Since the two fundamental quantities coronal brightness and magnitude of the photospheric field are a maximum near the Hale portion of sector boundaries and a minimum near the non-Hale portion of boundaries, we may expect that other aspects of solar structure and solar activity may be related to Hale boundaries and to non-Hale boundaries. Further study of this interaction between the sectorial aspect of solar magnetic structure and the zonal (activity) aspect of solar magnetic structure may improve our understanding of solar magnetism.

Acknowledgements

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Figure Captions

Figure 1 Schematic of the solar disk showing the portion of a sector boundary that is designated a Hale boundary. A Hale boundary is that portion of a sector boundary that is located in the solar hemisphere in which the change of magnetic polarity at the sector boundary is the same as the change of magnetic polarity from a preceeding spot to a following spot. The spot polarities shown in the small circles correspond to cycles 18 and 20.

Figure 2 Relative brightness in the northern hemisphere of the green coronal intensity on the Pic du Midi scale in sunspot cycles 18, 19 and 20 near (+,-) boundaries and near (-,+) boundaries. The vertical arrow indicates the time a sector boundary was observed at earth, and the vertical dashed line indicates the location of the boundary on the sun.

Figure 3 Separate analysis for low (-2.5^{o} to 17.5^{o}), middle (17.5^{o} to 37.5^{o}) and high (37.5^{o} to 57.5^{o}) solar latitudes of the brightness of the green corona above Hale boundaries (filled circles) and above non-Hale boundaries (open circles). The coronal brightness is a maximum above Hale boundaries and a minimum above non-Hale boundaries in all three latitude ranges.

Figure 4 (Top) Relative coronal brightness above a (+,-) boundary in the northern hemisphere as a function of time from 1947 to 1970. During cycle number 19 (1954-1964) this portion of the boundary was a Hale boundary and had maximum coronal brightness, while at other times it was a non-Hale boundary and had minimum coronal brightness. The change from Hale boundary to non-Hale boundary is seen to occur within a year near the time of sunspot minimum. The left scale shows brightness changes in per cent, and the right scale in density units.

(Bottom) Total brightness of the green corona as a function of time from 1947 to 1970. The units are arbitrary.

Figure 5 Average synoptic map of the magnitude of the photospheric magnetic field observed at Mt. Wilson during 1967 to 1973 near 104 (-,+) sector boundaries. The solid triangle indicates the observation of the boundary at earth, and the vertical line at central meridian indicates the location of the boundary in the photosphere. The contour interval is 1 gauss. At this time the northern portion of this boundary was a Hale boundary, and in the northern hemisphere the magnitude of the photospheric field is a maximum near the boundary. In the southern hemisphere the magnitude of the photospheric field is a minimum near the non-Hale boundary.

Figure 6 Same as Figure 5, except for 107 (+,-) sector boundaries.

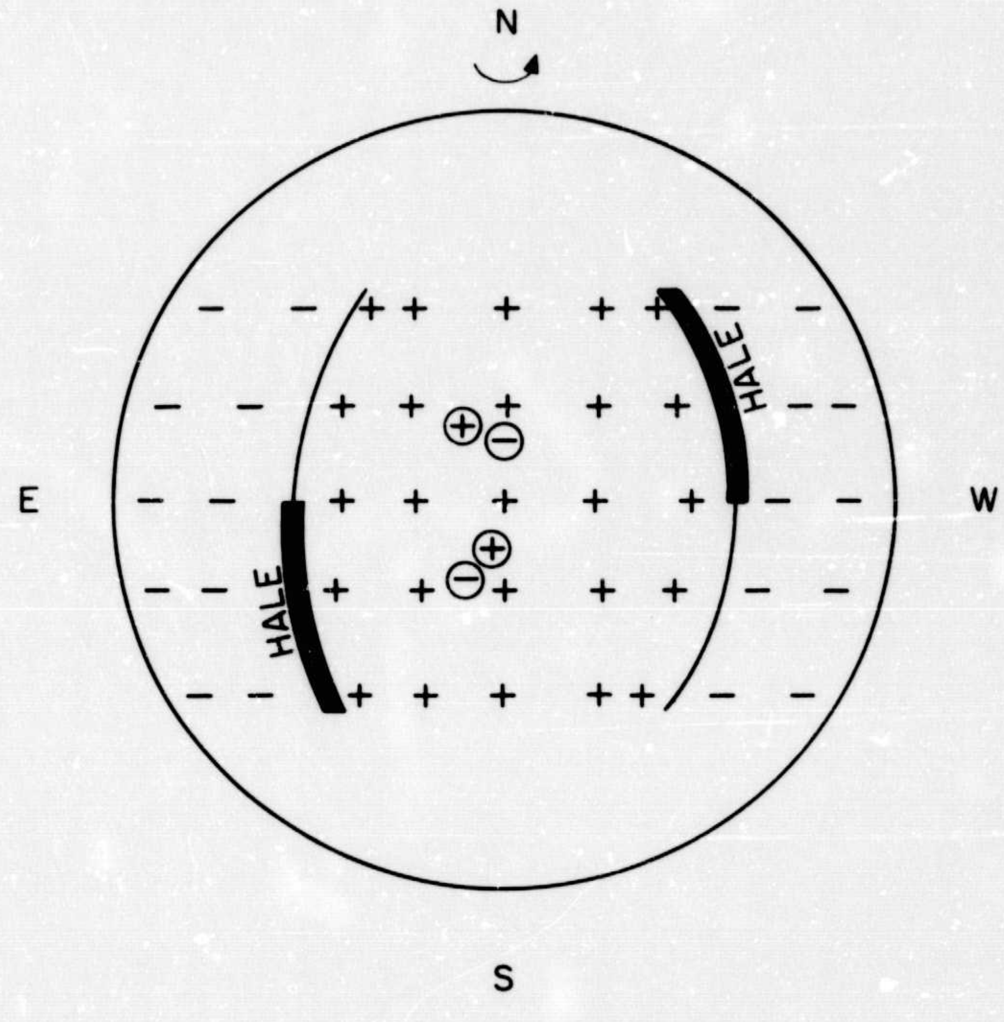


Figure 1

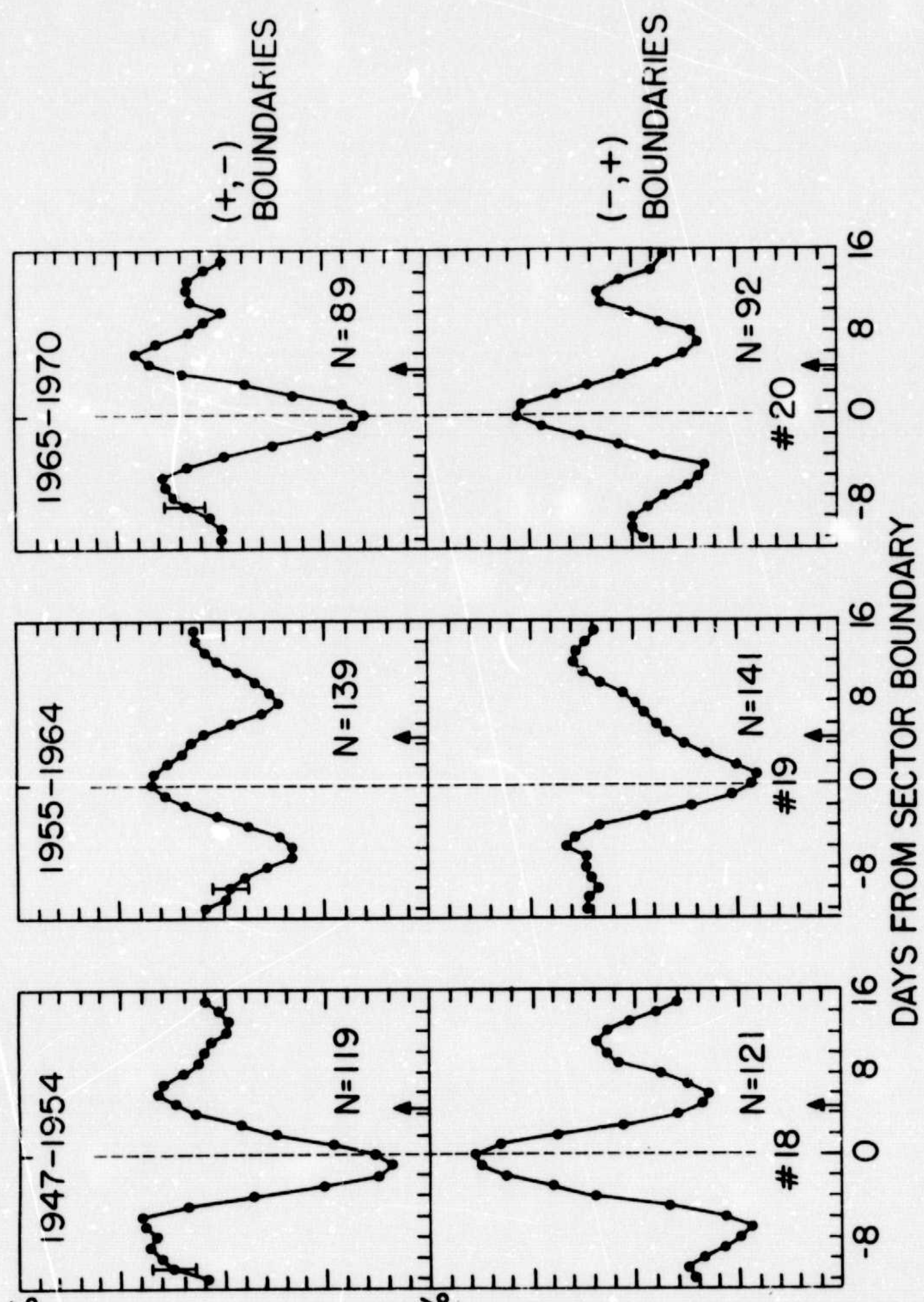

RELATIVE λ5303 CORONAL INTENSITY IN NORTHERN HEMISPHERE
20%
10
0
-10
%
10
0
-10
-20
1947-1954
N=119
N=121
#18
1955-1964
N=139
N=141
#19
1965-1970
N=89
N=92
#20
(+,-) BOUNDARIES
(-,+) BOUNDARIES
-8
0
8
16
DAYS FROM SECTOR BOUNDARY

Figure 2

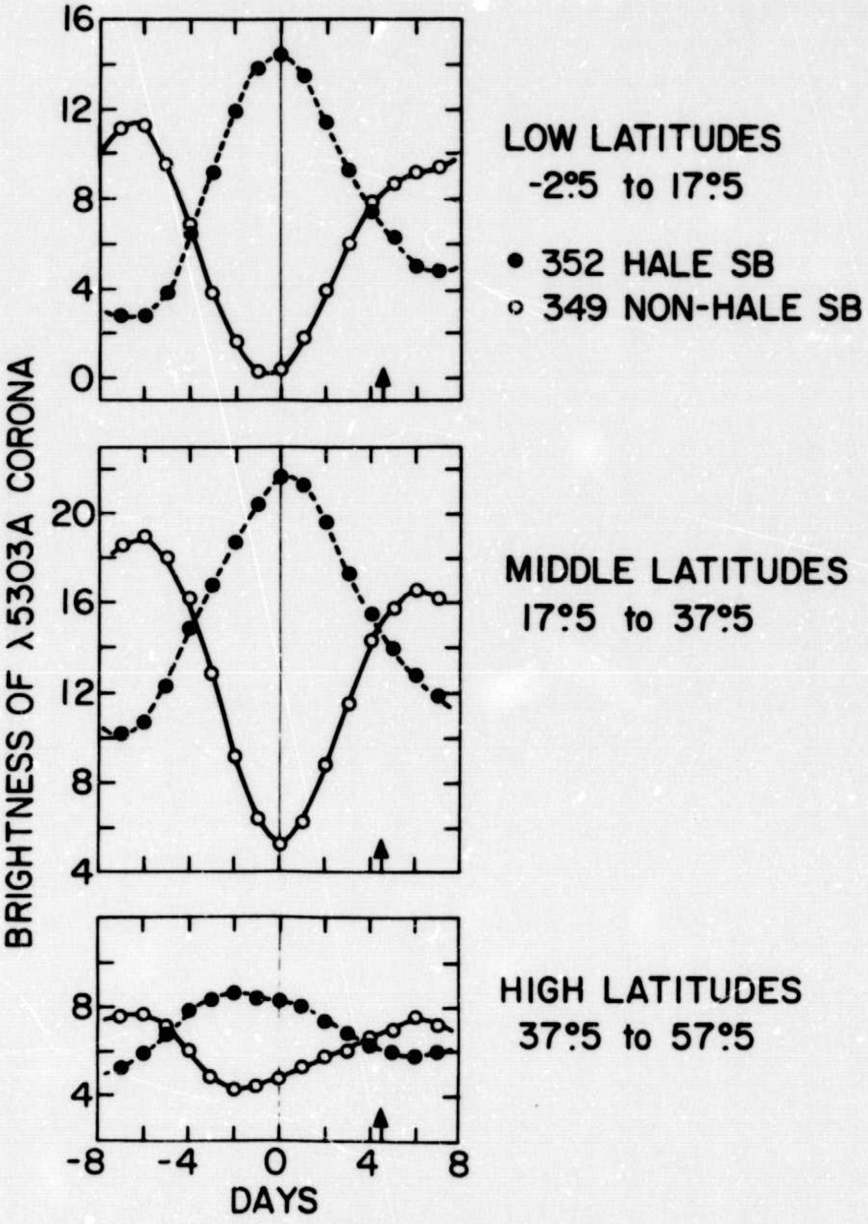
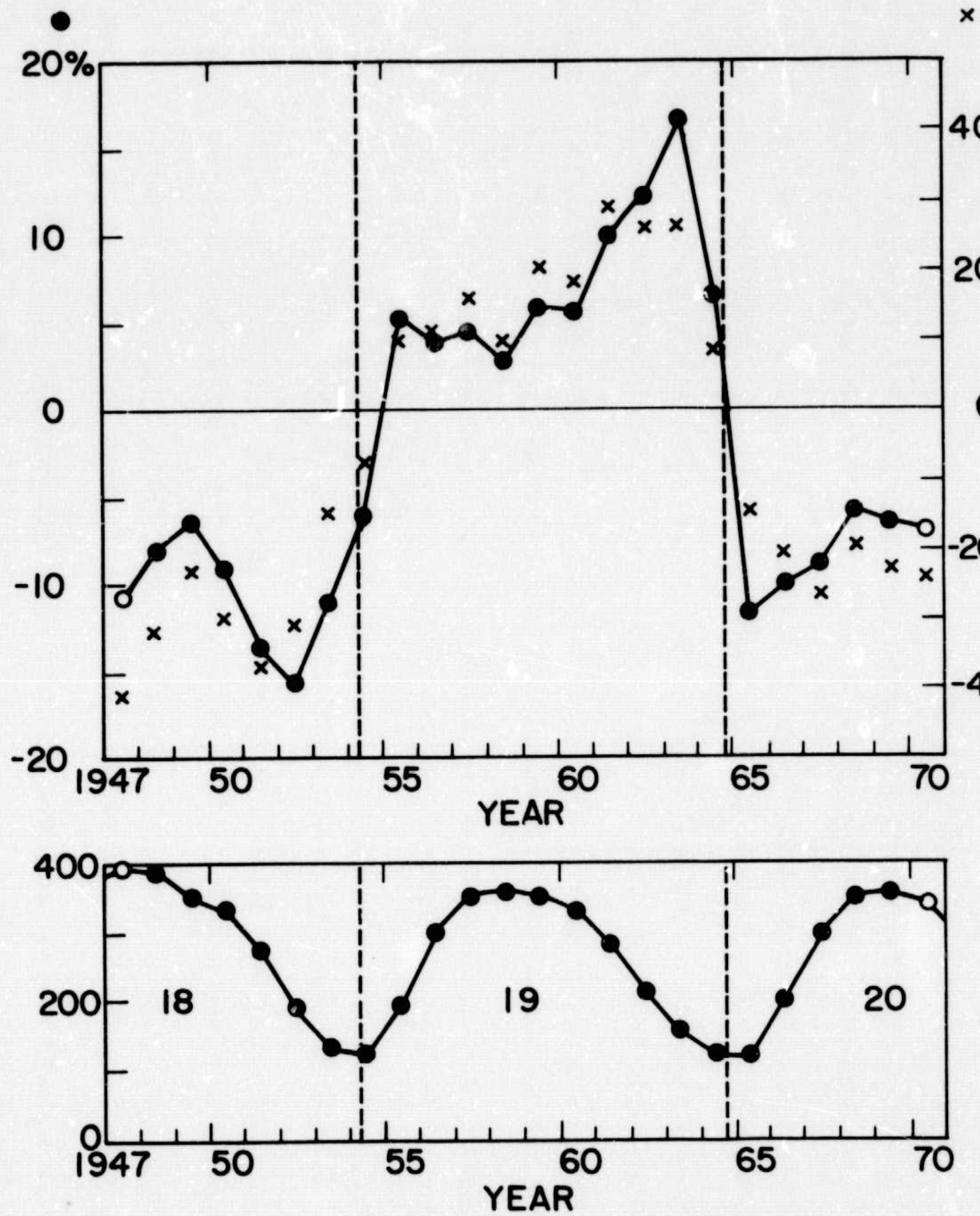

BRIGHTNESS OF λ5303A CORONA
DAYS
LOW LATITUDES
-2°5 to 17°5
● 352 HALE SB
○ 349 NON-HALE SB
MIDDLE LATITUDES
17°5 to 37°5
HIGH LATITUDES
37°5 to 57°5

Figure 3



●
×
20%
10
0
-10
-20
40
20
0
-20
-40
1947
50
55
60
65
70
YEAR
400
200
0
18
19
20
1947
50
55
60
65
70
YEAR

Figure 4

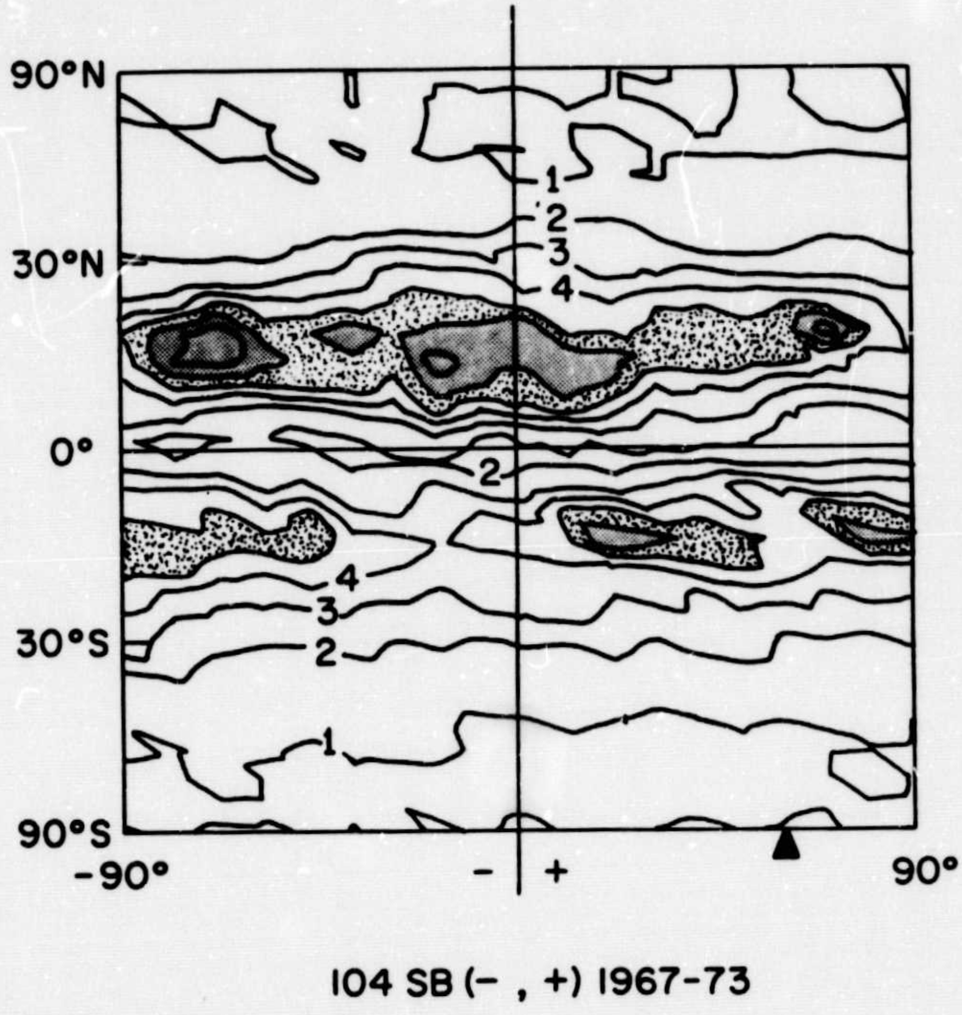


Figure 5

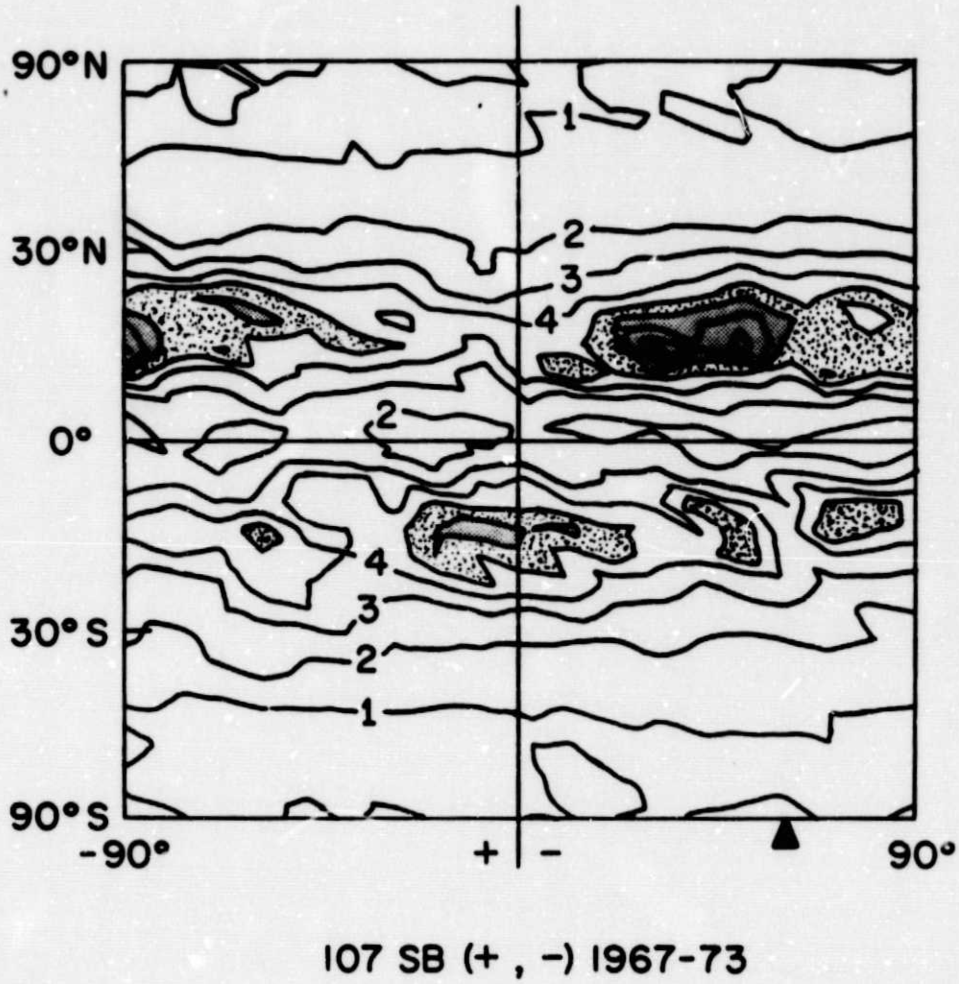


Figure 6