Current Theoretical Models and High Resolution Solar Observations: Preparing for ATST
ASP Conference Series, Vol. 286, 2003
A. A. Pevtsov and H. Uitenbroek, eds.

Relationship Between Magnetic Structures of Small and Large Sunspot Groups

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Abstract. Using the data on sunspot groups of life span (τ, in days) 2-12 day during 1874-1981 we find: (i) the average area (A, in millionth of solar hemisphere) of a spot group increases with τ as $A(\tau) = 15.24\ exp(\tau/4.48)$; and (ii) the number of spot groups (N) seems to decrease with τ as $N(\tau) \sim 2824\ exp(-\tau/5.38)$. From these and the relations found earlier among Sun's fractional radius (r), age (t) of the long-living (10-12 day) spot groups and life span (τ) of spot groups living 2-12 day, we draw the following inferences: (a) magnetic structures with magnetic flux $\Phi \geq 10^{22}$ Mx might be generated near base of the convection zone, (b) many of the magnetic structures may be fragmenting or branching into smaller structures while rising through the solar convection zone, and (c) magnetic structures with $\Phi < 10^{22}$ Mx might be the fragmented or branched parts of the larger magnetic structures. These inferences are consistent with the proposals of some theoretical models.

1. Introduction

The daily area of a sunspot (or sunspot group) is one of the most important parameters used to describe the spot (or spot group) development. The area of a spot (or spot group) is closely connected with the magnetic flux of the spot (or spot group). So, the development of the spot (or spot group) area reflects the development of the magnetic field. It is well known that larger spot groups also live longer. The life span, τ (in days), of a spot group seems to be related to the maximum area, A_{max} (in mh, millionth of solar hemisphere), in the following way, (a rough measure attained by the rule-of-thumb, see Bray & Loughhead 1964) :

$$\tau = 0.1A_{max}.$$

Earlier, using Greenwich data on sunspot groups during 1874–1939 we studied dependence of mean rotation frequency of a spot group on its age (t) and dependence of 'initial rotation frequency' of a spot group on its life span (τ). These were compared with the dependence of plasma rotation frequency, $\Omega(r, \lambda)$, on the radial distance (r) and latitude (λ) as determined from helioseismology. From this we obtained the following relations, (Javaraiah & Gokhale 1997):

$$r(t) = (480.6 \pm 0.7) + (20.9 \pm 0.1)t \qquad (1)$$

for the spot groups of life spans 10–12 days in latitude $10^\circ - 20^\circ$; and

$$r_0(\tau) = (696.5 \pm 0.6) - (20.9 \pm 0.1)\tau \qquad (2)$$

for the spot groups of life spans 2–12 days in the entire sunspot latitude belt. Here $r(t)$ and $r_0(\tau)$ are in Mm, the $r_0(\tau)$ represents 'initial anchoring' depths of the magnetic structure (flux ropes) of spot groups of life span τ and the $r(t)$ represents anchoring depths of the magnetic structures of 10-12 days living spot groups at their age t. These relations imply the following possibility: (i) the magnetic structures which yield spot groups with life spans 10–12 days are initially anchored near the base of the convective envelope; (ii) in latitude interval $10^o - 20^o$ these structures rise at a rate $\sim$ 21 Mm per day, as the spot group ages; and (iii) the magnetic structures of spot groups which live successively shorter by 1 day are initially anchored in layers successively shallower by $\sim$ 21 Mm.

Recently, (Javaraiah 2001), we have analyzed the Greenwich data during 1874–1976. The relation (1) above, is found to be more realistic for spot groups with average area $A \geq 130$ mh. This suggests that the area-life span relation of spot groups may not be linear. In order to check this we studied area-lifespan relation of spot groups. We also studied distribution of number of spot groups with respect to life spans. The results of these studies with $r_0 - \tau$ and $r - t$ relations mentioned above seem to be providing an important information on how the generation of magnetic structures of small (or short-lived) groups is related with those of large (or long-lived) groups. In this paper we have presented these results.

2. Data and Method of Analysis

Recently, the upgraded Greenwich data (1874–1976) and NOAA/UASF data (1977–1981) became available to us. These data were compiled by the National Geophysical Data Center, USA. These data included time, heliographic latitude (λ) and longitude, corrected whole spot area (in mh) and central meridian longitude (CML) for each day of observation, besides other parameters, for all the spot groups observed during 1874–1981.

Let t_1, t_2,......,t_n be the times at which a given spot group was observed and A_1, A_2, ...A_n be its corresponding area values. Considering t_1 as the time of 'birth' and t_n as the time of 'death' of the spot group, the lifetime or life span (τ, in days), the maximum area (A_{max}) and the average area (A) of the spot group are determined as follows:

$$\tau = t_n - t_1,$$

$$A_{max} = Max\{A_i,\ i = \ 1, ...n\},$$

$$A = 1/n \Sigma A_i\ ,\ i = 1, n.$$

The data reduction is same as described in Javaraiah & Gokhale (1997). For our present purpose also it is essential to know the the life spans of spot groups corrected up to $\sim$ 0.5 day. This is possible only for spot groups of life spans up to 12 days. The available Greenwich data have not included identifications of recurrent spot groups. Hence, it is not possible to determine the life spans of recurrent spot groups. We have excluded the entire data on those spot groups which have $|CML| > 75°$ on any day of their life. This also leads to elimination of the second and the subsequent disk passages of the recurrent spot groups. Thus, all spot groups with identifiable first and last days have life spans $\leq$ 12

2003ASPC..286..325J

Table 1. The number (N) and the average area (A, in mh) of sunspot groups with different specified life spans (τ, in days) in different 10^o latitude intervals and in whole sunspot latitude belt (northern and southern hemispheres data is combined) during 1874–1981.

τ	latitude intervals							
	0° – 10°		10° – 20°		20° – 30°		Whole belt	
	N	A	N	A	N	A	N	A
1.5	620	21.0±1.1	1119	20.9±0.7	530	19.5±0.9	2347	20.5±0.5
2.5	444	26.8±1.3	789	29.2±1.2	372	28.3±1.4	1654	28.4±0.7
3.5	339	36.6±2.2	679	35.7±1.6	284	35.9±2.0	1358	35.7 ±1.1
4.5	286	40.4±2.7	529	41.6±1.9	250	43.5±2.9	1100	41.9 ±1.4
5.5	272	56.4±5.0	469	52.0±2.7	203	53.7±6.4	979	53.7 ±2.3
6.5	224	62.4±4.3	428	61.1±3.5	176	64.0±5.7	855	61.7 ± 2.4
7.5	177	68.6±4.6	348	75.8±3.8	161	79.5±5.8	708	74.9 ±2.6
8.5	153	101.1±7.8	331	81.4±4.0	134	90.1±7.0	636	87.9 ±3.2
9.5	161	108.1±6.7	297	129.7±8.4	118	112.8±11.7	596	119.5 ±5.1
10.5	141	164.1±11.2	289	195.3±11.4	122	185.9±18.3	569	185.7 ±7.6
11.5	40	206.1±29.0	96	205.6±16.5	54	218.6±19.9	198	210.0 ±11.4

days. The spot groups were further binned into latitude intervals of width 10° each. In order to have better statistics, groups in the same latitude intervals in the northern and southern hemispheres were taken in combination. We have used spot group average area because it is statistically more accurate than the spot group maximum area. In Table 1 we give the total number (N) and the average area (A) of the spot groups with different specified life spans in three latitude intervals of 10° each and also in the entire sunspot latitude belt during 1874–1981.

3. Area-Life Span Relation of Sunspot Groups

In Table 1 it can be seen very clearly that the larger spot groups live longer than the smaller spot groups, and the number of small (or short-lived) spot groups is larger than the number of large (or long-lived) spot groups. However, A and τ, and also N and τ (or A), seem to be not linearly related. Figures 1(a) and 1(b) show the correlations between $ln(A)$ and τ, and between $ln(N)$ and τ, respectively, determined from the values (given in Table 1) of A, τ and N. In these figures the solid lines represent the relation between $ln(y)$ and τ obtained from linear regression analyses of the form $ln(y) = p + q\tau$ for $y = A$ and $y = N$. The corresponding values of the intercept (p), slope (q) and correlation coefficient (R) are given in Table 2. In case of $A - \tau$ relation the magnitudes of R are high in all latitude intervals. They are also considerably higher than those given in the brackets for regression of the form $y = p + q\tau$. The correlation between N and τ is substantially lower than that of between A and τ. The $N - \tau$ relation seems to be latitude dependent. The form $ln(N) = p + q\tau$ seems to fit better in higher latitudes.

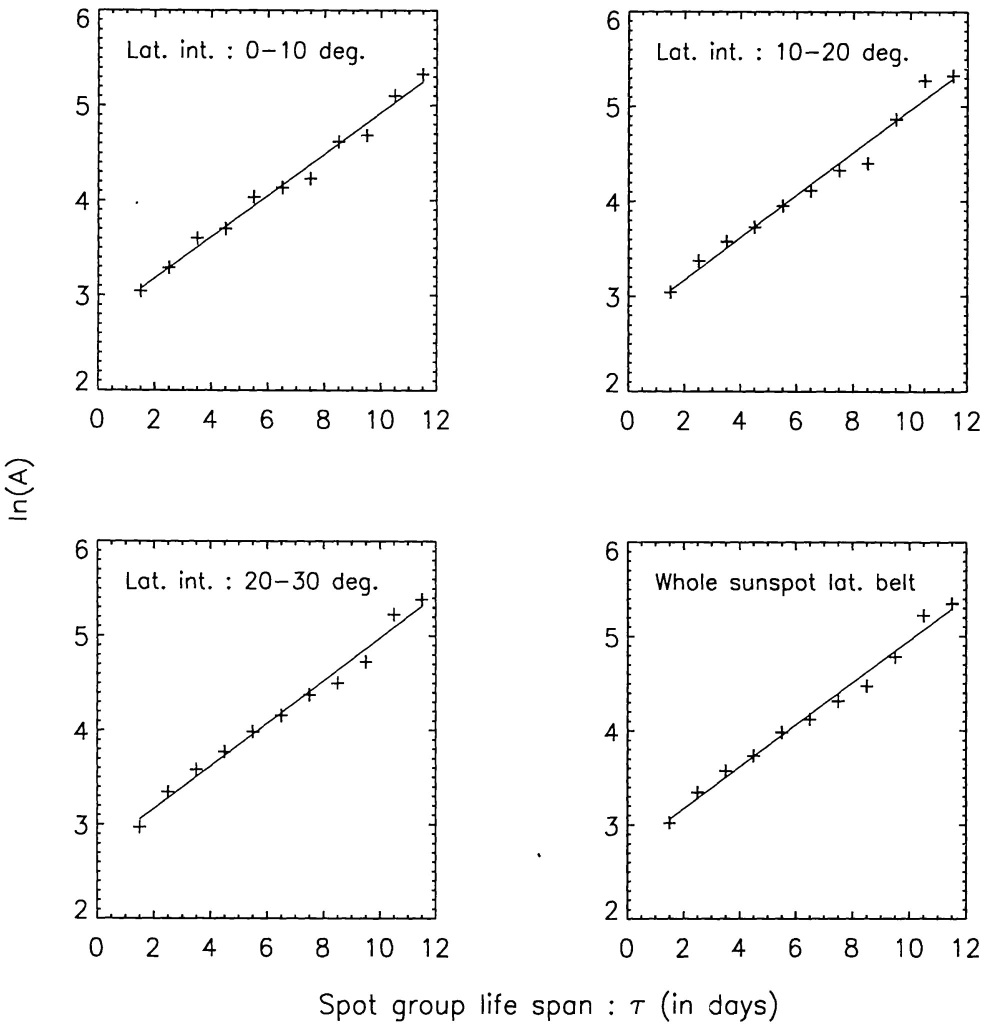

Figure 1(a).

Figure 1. Plots of (a) $ln(A)$ against τ and (b) $ln(N)$ against τ, for the values of A, τ and N given in Table 1. In (a) the *solid lines* represent the relation between $ln(A)$ and τ, and in (b) they represent the relation between $ln(N)$ and τ, obtained from the linear regression analyses (see Table 2).

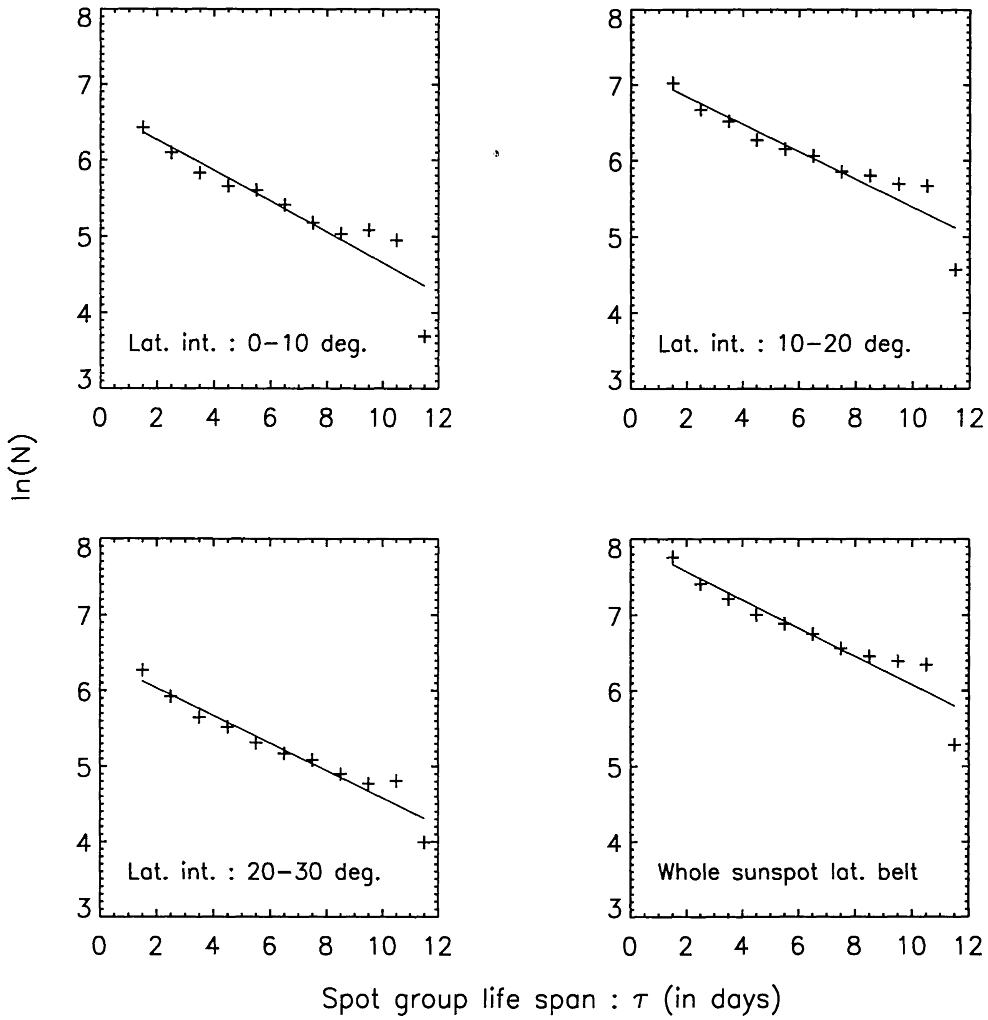
ln(N)
Lat. int. : 0–10 deg.
Lat. int. : 10–20 deg.
Lat. int. : 20–30 deg.
Whole sunspot lat. belt
8
7
6
5
4
3
0
2
4
6
8
10
12
Spot group life span : τ (in days)

Figure 1(b).

Table 2. Values of the coefficients (p and q) in the equation $ln(y) = p + q\tau$ and correlation coefficient (R) for $y = A$ and $y = N$ determined from the method of least–square fit to the values of A, N and τ given in Table 1. The values of R for regression of the form $y = p + q\tau$ are given within the brackets.

	latitude intervals			
	0° – 10°	10° – 20°	20° – 30°	Whole belt
For $y = A$:				
p	2.745±0.061	2.725±0.078	2.713±0.066	2.724±0.062
q	0.217±0.008	0.224±0.011	0.226±0.009	0.223±0.008
R	0.9933 (0.9296)	0.9896 (0.9180)	0.9928 (0.9200)	0.9933 (0.9228)
For $y = N$:				
p	6.671±0.199	7.207±0.168	6.399 ±0.118	7.946 ±0.159
q	-0.202±0.027	-0.182±0.023	-0.182±0.016	-0.186±0.022
R	-0.9254 (-0.9318)	-0.9331 (-0.9329)	-0.9657 (-0.9208)	-0.9429 (-0.9317)

From Figures 1(a) and 1(b), and from Table 2, we can draw the following inferences for spot groups with life span 2–12 days in all latitudes:

(i) the average area of a spot group increases exponentially with increasing spot group life span, or

$$A(\tau) = 15.24\ exp(\tau/4.48), \tag{3}$$

(ii) the number of spot groups seems to decrease exponentially with increasing spot group life span, or

$$N(\tau) \sim 2824\ exp(-\tau/5.38). \tag{4}$$

In the inferences (i) and (ii), above, the values of the parameters in the expressions given in brackets are determined from the data in the entire sunspot belt. However, in case of $N - \tau$ relation the values of the intercepts (and correlation coefficients) differ significantly in different latitude intervals. In case of $A - \tau$ relation, there are no significant differences in the values of the intercept, slope, and correlation coefficient in a given latitude with the corresponding values in the whole belt (cf., Table 2). Thus, the expression given in inference (i) holds good for all latitudes.

4. Relationship Between Small and Large Magnetic Structures

Interestingly, the magnitudes of the slopes in $r - \tau$ and $r - t$ relations are equal (cf., Equations 1 and 2). It follows that for spot groups with $\tau \leq 9.5$ days

$$r_0(\tau) \approx r(10.5 - \tau). \tag{5}$$

This means that in latitudes 10° − 20° the 'initial anchoring' of the magnetic structures of spot groups with $\tau \leq 9.5$ days is at the same depth where the anchoring of the magnetic structures of spot groups with life span $\tau = 10.5$ days reaches in $t = (10.5 - \tau)$ days. Also, the equations (2) and (3) imply the exponential relation:

$$A \approx 130\ exp(-H/95), \tag{6}$$

where H, in Mm, is the height above the base of the convection zone. For $A = 130$ mh the corresponding amount of magnetic flux $\Phi = 10^{22}$ Mx (see also Wang & Sheeley, 1989). From these two facts (cf., Equations (5) and (6)) we draw the following inferences:

(a) magnetic structures with $\Phi \geq 10^{22}$ Mx might be generated near base of the convection zone,

(b) many of the magnetic structures may be fragmenting or branching into smaller structures while rising through the solar convection zone, and

(c) magnetic structures with $\Phi < 10^{22}$ Mx might be the fragmented or branched parts of the larger magnetic structures.

These inferences are consistent with the proposals of some theoretical models (e.g., Parker 1979). Such an inference would also account for decrease of N with τ (suggesting increase of N with H).

[Note: The $r - t$ relation (Equation (1)) used here is mainly applicable to the spot groups of life spans 10-12 days in the latitude interval 10° − 20°. However, by large extent it is also applicable to the spot groups in the whole sunspot latitude belt (Javaraiah 2001).]

5. Discussion

In Figure 1(b) one can see that there exist large deviations between estimated and observed values of the last 2 or 3 points (at $\tau \geq 9$ days, $A > 130$ mh or $ln(A) > 4.87$). In fact these points seem not to fit to the exponential forms suggested in Section 3 (inference (ii)). This is because magnetic structures of the spot groups with $\tau > 9$ days and $A > 130$ mh might be generated directly from the basic mechanism which generates the magnetic field for solar activity near the base of the convection zone. Drag force may be less on these large magnetic structures (e.g., D'Silva & Howard 1994). These structures (large magnetic flux tubes) seem to rise more radially (Javaraiah 2001). Regarding the inference (b), above, further studies will be needed to determine whether these large magnetic structures rise as closed loops (and undergo fragmentation) or remain rooted at the base of the the convection zone (and undergo branching in their upper parts).

To the best of our knowledge, so far exponential relationship of areas of active regions to their life spans is not reported. However, some authors have shown that the size distribution of active regions is close to exponential (e.g., Tang, Howard, & Adkins 1984). Some other authors have shown that it is close to power law or log–normal distribution (Harvey & Zwaan 1993; Bogdan et al. 1988; Howard 1996). Gokhale & Sivaraman (1981) have shown that the distribution of sunspot groups with respect to maximum area may not be fitted by a simple one-parameter distribution such as single power law or an exponential law. The $N - \tau$ relation found in the present analysis is also less reliable than the $A - \tau$ relation.

It is important to note that the internal rotation of the Sun is varying with time besides its radial and latitude dependence (e.g., Howe et al. 2000a, b). The solar rotation rate determined from spot groups also varies with periods similar to those of solar magnetic activity (e.g., Javaraiah & Gokhale 1995; Javaraiah & Komm 1999; Javaraiah 2000, 2001, 2002). In determining the rotation frequencies of spot groups we had used 66 years data (Javaraiah & Gokhale 1997). The helioseismic data covers only about 1/2 of the solar cycle. The results and the inferences presented in Sections 3 and 4, above, represent only the average behavior of spot groups over 100 years.

Recurrent spot groups during their second and later appearances are not included in this study. It should be of interest to see how the rotation frequencies of the spot groups living longer than 12 days vary in time and how their areas and life spans are related.

Acknowledgments. I am thankful to Prof. M. H. Gokhale for discussion and useful suggestions, and to our director for the sanction of my deputation to the workshop. I thank SOC and LOC for the opportunity and invitation for the workshop. I gratefully acknowledge to the Asian Office of Aerospace Research and Development (AOARD), Tokyo, Japan, which sponsored my participation in the workshop.

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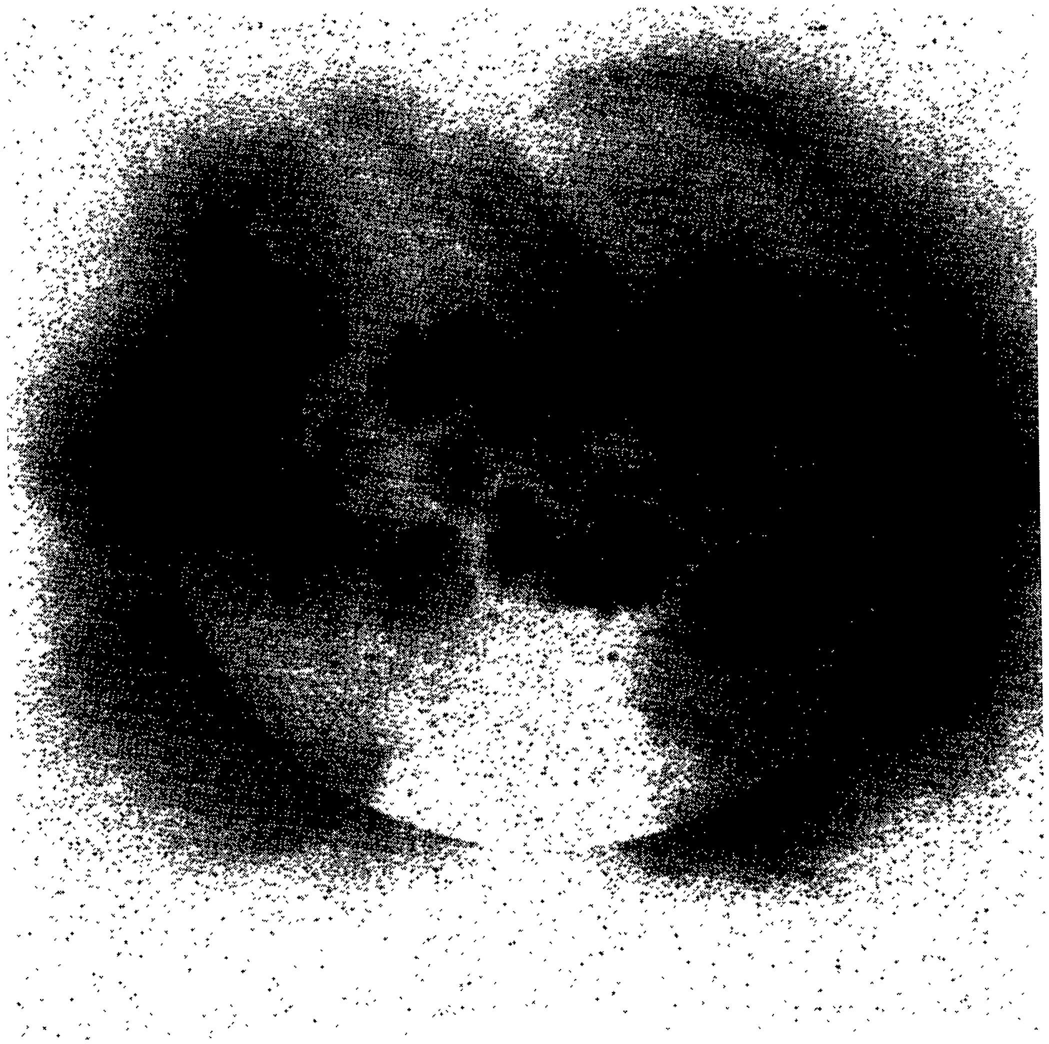
Part 4

Chromosphere and Corona



Solar corona observed by soft X-ray telescope on board of Yohkoh satellite.