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Interpreting the growth and destruction of a large long-duration solar active-region complex

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Abstract. In a companion paper, we show that the large limb flare and coronal mass ejection of July 9, 1982, and other energetic events that followed through September 4, 1982, represent the final phase in the evolution of a large active-region complex (Jordan et al. 1997).

In this paper, we review the long-duration evolution of this complex. We begin by showing that, before its final phase, new activity in the form of renewed flux continued to appear for nearly two years, progressively complicating the field topology. Observations suggest that the source of this flux rotated almost as a rigid body. Evidence is presented that, during the final phase of large-scale eruptions, either the connection with the underlying source of flux is broken, or the source itself has changed. After the flare and CME of September 4, 1982, the magnetic field topology of the entire complex was greatly simplified, and the area of former activity was replaced by a large coronal hole. We conclude that this evolution and destruction of a large long-duration active-region complex is a characteristic feature of how the global magnetic field of the Sun changes during the solar cycle.

Key words: Sun: magnetic field – Sun: activity – Sun: coronal hole – Sun: flares

1. Introduction

The eruptive processes in active region NOAA 3804 (Carrington's rotation (CR) No 1724), studied in Jordan et al. (1997), represent the most energetic events that occurred in the evolution of a large-scale activity complex that formed over a period of nearly two years during 1981 - 1982. Three rotations after the July 9, 1982 event, the magnetic configuration of this complex changed rapidly. Only two rotations later it was gone, and had been replaced by a large distinct coronal hole in the same area of the solar surface. Here we describe the evolution of this complex before, during and immediately following the phase of maximum activity.

2. Gradual formation of the large activity complex and its sudden end

2.1. Numbers and areas of northern-hemisphere active regions adjacent to Carrington longitude L = 321° during 39 consecutive CMPs

To estimate levels of activity, we used the Russian bulletin Solneshnye Dannye for 1981-1983, and studied the Central Meridian Passages (CMPs) of the Carrington heliographic longitude L = 321°, the center of gravity of NOAA 3804, for the three year period 1981 - 1983. From the Daily Charts of the Sun and The Daily Charts of the Magnetic Fields of Sunspots, we determined for each rotation the number of active regions visible in the northern hemisphere during the CMP of the mentioned L, and lying in the interval DL = 220° - 360° and 0° - 60°. For each active region, we took the heliographic longitude and latitude of its center of gravity and determined the maximum area reached during its disk passage, expressed in millionths of the solar hemisphere. The first CMP considered occurred on January 15, 1981 (Julian Date [2445]619.92), and the last one occurred on November 18, 1983 (Julian Date [2445]1656.77).

Constructing a grid of heliographic longitudes occupied by these active regions at the CMP of L = 321° during the given time interval, we see from Fig. 1 a very high concentration of active regions in the longitudinal interval DL = 300° - 330° before the September 1982 rotation. After that rotation, no further new activity developed in this interval during the period studied. If we determine for this same longitudinal interval the total area of all active regions for all of the above CMPs of L = 321° during this period, we obtain the result illustrated in Fig. 2. There we see a progressive growth of this total area until Julian Date 1165.64, or July 15, 1982. The effect is even more pronounced in the accompanying plot in Fig. 2 of the mean area of these active regions. All active regions disappeared from this longi-

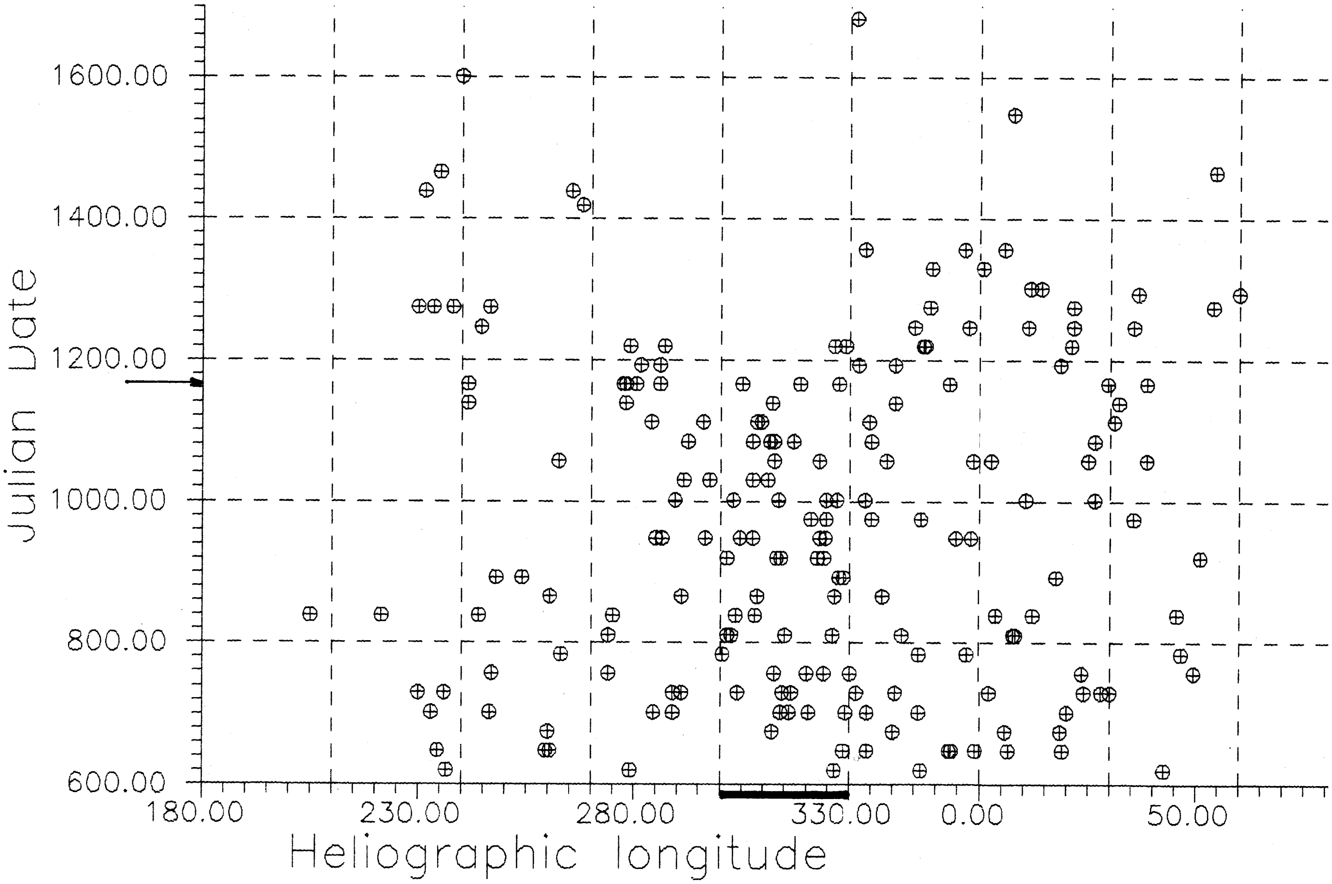

Fig. 1. Occupation by active regions of the grid of heliographic longitudes during Julian Dates from [2445]619.92 (January 15, 1981) till [2445]1656.77 (November 18, 1983). The most interesting interval of longitudes is indicated. The CMP of the region studied occurred on [2445]1165.96 (July 15, 1982).

tude interval the third rotation after the CMP of July 15, 1982, at least until the end of 1983.

On the same daily maps of solar activity on the days of CMP of L = 321°, we see a progressive concentration of sunspot activity into one region with its peaks in NOAA 3776 and its successor NOAA 3804, followed by its dispersion in longitudes as it rapidly diminishes and finally disappears altogether. We note also a continuous shift of the center of gravity of activity westwards.

2.2. *Large-scale development on the $H\alpha$ and magnetic synoptic charts*

If we compare the Sacramento Peak Observatory $H\alpha$ synoptic charts for DL between 210° - 360° and 0° - 70° for successive CRs Nos 1721 - 1738, with the Stanford Solar Observatory's magnetic synoptic charts over the same DL range for this period, we observe the following developments. On both sets of charts before July 1982 (CR 1724), there is a similar gradual evolution of the magnetic field to a more complex structure in the longitudinal interval 300° - 330°. We then see a rapid weakening and decrease in area of the magnetic field over this entire region (Fig. 3). Further insight into the nature of this active-region complex is gained if we consider the large longitudinal filament that marks one of its boundaries, and is discussed in our companion paper (Jordan et al, 1997). This filament resembles one of the "pivot lines" described by Mouradian et al. (1987, 1990). These lines are filaments found to trace the boundaries of regions of continuously developing activity that rotate rigidly around associated "pivot points," in contrast to filaments that rotate under the influence of the differential rotation.

In the longitudinal interval 300° - 330°, Fig. 3 reveals a large positive unipolar region in the northern hemisphere in CR 1722. This region not only expands poleward by about 20° in latitude in just two rotations, but also crosses the solar equator in successive rotation 1723, and by rotation 1725 has formed a completely connected parabola-like positive polarity feature joining both polar regions. This global feature reaches the polar latitudes through the combined effects of magnetic field expansion and differential rotation, and is formed by the successive joining of positive polarity fields of individual active regions (see Figs. 7a, b in Bumba & Hejna 1987). Like the "pivot line" filament described above, the feature rotates like a rigid body for at least 5 rotations, in contrast to the smaller unipolar regions from which it was formed, and whose dynamics are influenced by the action of differential rotation.

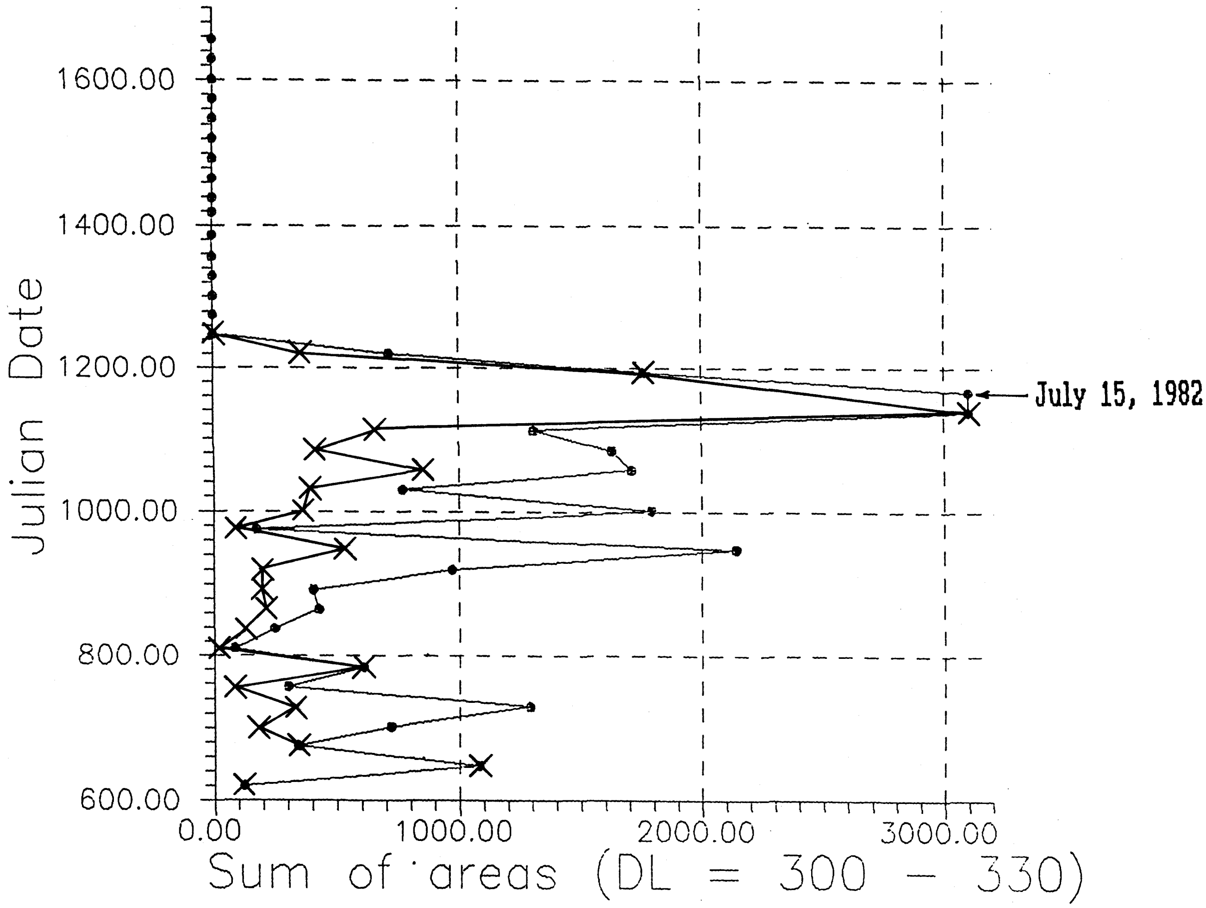

Fig. 2. Graphs of the sum of the maximum area (light line connecting points) and of the mean area (heavier line connecting crosses) of all active regions observed in the longitude interval 300° - 330° for the same time interval as in Fig. 1. Time is running upwards. Mean area is the total summed area divided by the number of active regions.

A similar negative unipolar region is seen to develop in the northern hemisphere just westward from the extended positive-polarity unipolar region already described. By rotation 1732, a large negative-polarity northern-hemisphere coronal hole has appeared in the northern hemisphere. By rotation 1735, it has clearly crossed the equator and has filled much of the region formerly occupied by the large activity complex (Fig. 3). This coronal hole seems to be the last evolutionary stage of the former activity complex, although it has shifted about 20° westward.

It should also be noted that the global magnetic field exchanged its polarity with respect to the solar equator and also to the large filament that traced its main polarity boundary, as shown in the lower-latitude regions on the Stanford maps for rotations 1722 and 1735 (Fig. 3). This reveals a complete global reconstruction of solar magnetic fields in both hemispheres during the period studied.

2.3. *Relationship of the activity complex to the global magnetic field during the phase of maximum activity*

The peak activity level of the long-duration complex was reached during June and July of 1982, as seen in Fig. 2. During the June rotation, CR 1723, active region NOAA 3776 contained the largest sunspot group of cycle 21 observed after July 1978 and yielded a large number of flares that were observed in both the visible and in the X-ray range (Bumba & Klvaňa, 1997).

We can see a striking global configuration of the Sun's background magnetic field on the magnetic synoptic maps from the Wilcox Solar Observatory during rotations 1722 and 1723, when the active regions passed through the central meridian (Bumba & Klvaňa, 1997, Figs. 1,2). The activity zone of the whole Sun was covered by a global bipolar magnetic pattern, with the leading positive-field region occupying almost half of the area and the following negative-polarity part occupying the other. NOAA 3776 originated on the polarity boundary of this bipolar region, in its northeastern part. The local polarity boundary between the leading and following fields of NOAA 3776 coincides exactly with the northeastern part of the global boundary of the global magnetic pattern, and has the same signs as the global pattern of leading and following fields. Thus NOAA 3776 and its successor NOAA 3804 were "twice bipolar" (locally and globally), and we can expect the distribution of their magnetic lines of force to be dipole-like to a high degree. Their position on the boundary of a global magnetic field must be the result of

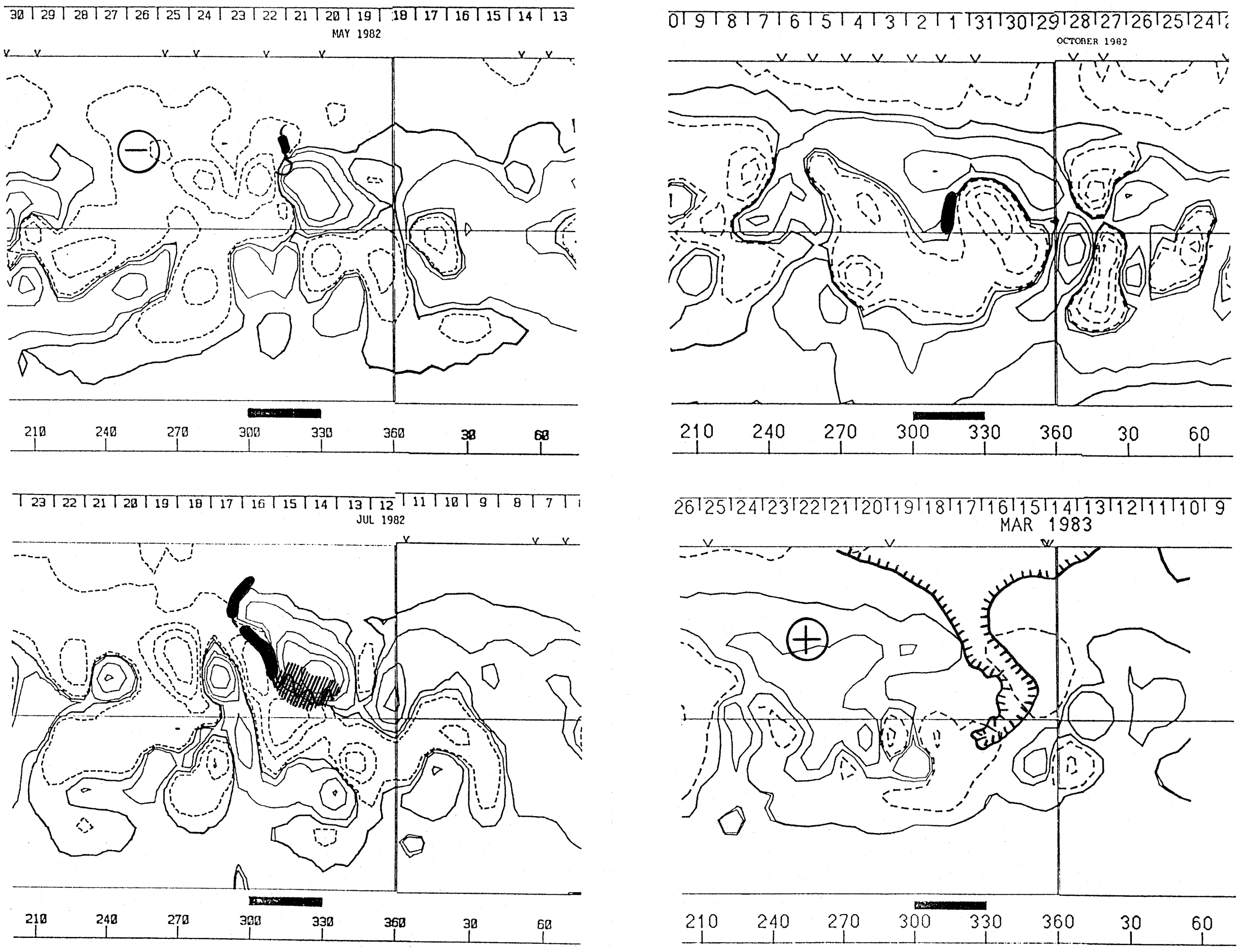

Fig. 3. Parts of the Stanford Solar Observatory magnetic synoptic charts for the DL range (210° - 360° and 0° - 70°) for rotations Nos: 1722/21, 1724/23, 1728/27, 1733/32, overlapped by the schematically drawn parts of filaments (black lines) and the coronal hole (on the last map), visible on the $H\alpha$ synoptic charts, and mentioned in the text.

long-lasting activity development in the area, as illustrated in Fig. 2.

The maps of the longitudinal magnetic component obtained by the Ondřejov magnetograph during three days of the July 1982 CMP of this activity complex (Fig. 4) show a large region of positive polarity extending in the east-west direction. This region is surrounded by large islands of negative polarity, also oriented mainly east-west and lying southwards of the positive-field region. The numerous negative-polarity islands around the main region of positive polarity indicate that there exist many rapidly developing regions with high magnetic field gradients capable of enhancing strong chromospheric and coronal activity. We also see in Fig. 4 the gradual weakening and decrease in area of this longitudinal field, especially in its eastern part where the islands of negative polarity successively diminish, thus reducing the field gradients. The curvature of the boundary increases toward the east.

While the main local magnetic field boundary in Fig. 4 is almost parallel to the equator for most of its length, there is a secondary magnetic field boundary bordering the eastern edge of the positive polarity region and running essentially north-south. It is highly probable that the erupting loops observed during the July 9 event (Jordan et al, 1997) developed above the main local magnetic-field boundary that runs perpendicular to the axis of the large north-south quiescent prominence/filament mentioned earlier. This feature lies above the eastern secondary magnetic boundary which coincides with the large-scale magnetic field boundary in that region.

On June 18, the sunspot group was strongly concentrated into one cluster around a large complicated spot, while on July 15 the spots were extended into a long chain almost parallel to the equator, although close to the east limb they exhibited a more longitudinal orientation. There was a rapid increase in the group's area and in the spot magnetic field intensities during the first four or five days after July 15, followed by a decrease in the group's area and its gradual disintegration, along with a corresponding decrease of the spot-field intensities.

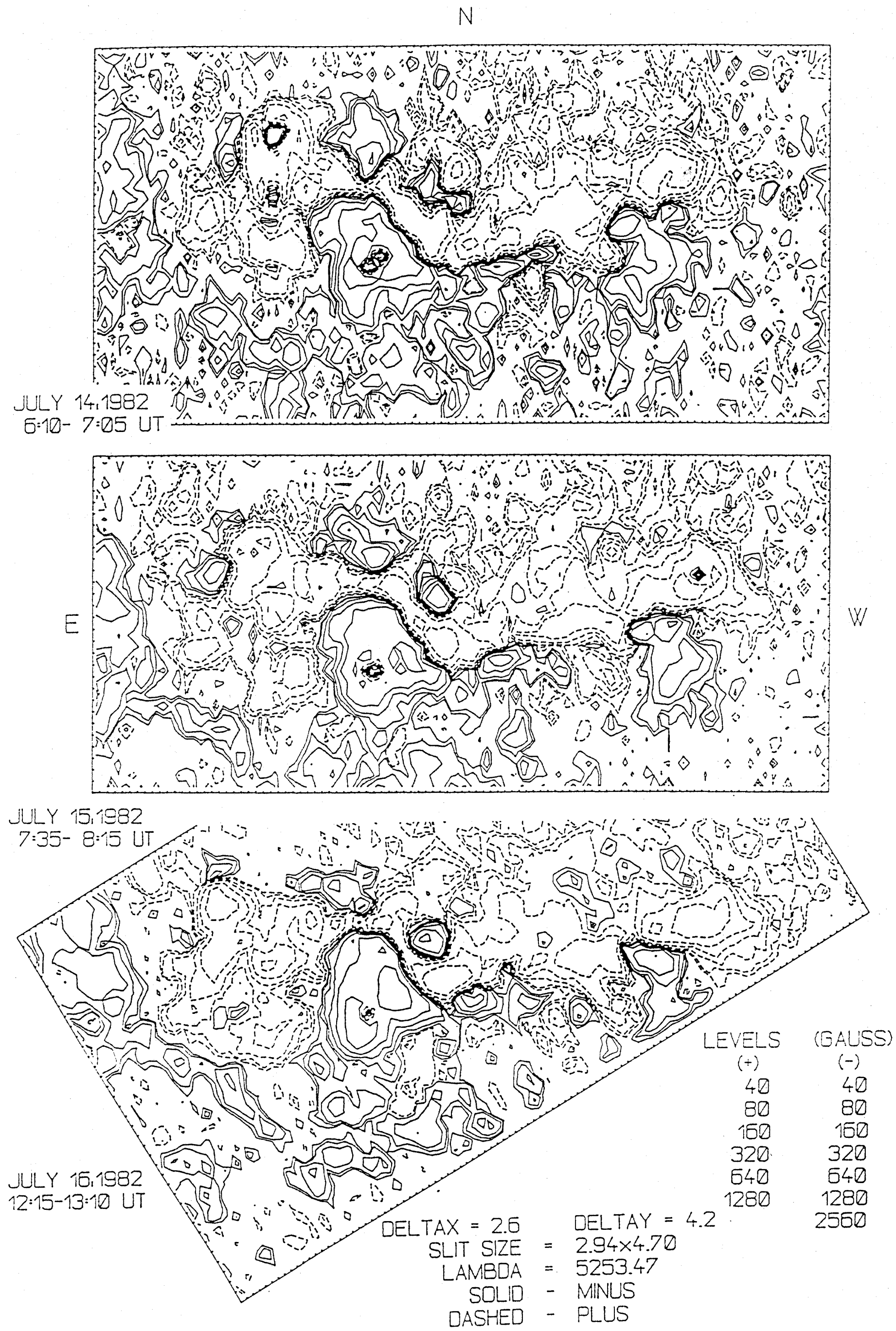

Fig. 4. Best maps of the longitudinal magnetic field component obtained with the photoelectric magnetograph at the Ondřejov Observatory on July 14, 1982 (06:10-07:05 UT), July 15 (07:35-08:15 UT), and July 16 (12:15-13:10 UT). Positive polarity is drawn by dashed lines; negative polarity by solid lines.

3. Discussion

This work continues earlier studies of the evolution of large-scale magnetic patterns which reached their climax in the formation of large complex active regions that produced numerous energetic white-light and proton-emitting flares (Bumba & Sýkora 1974, Bumba 1982, Bumba & Hejna, 1987). In each case the time-scale of the process was of the order of one year or more, and in all cases the local magnetic fields were transformed step by step from a relatively simple configuration into a more complex one. A number of processes were involved in this transformation: the appearance of new magnetic flux in active regions or in active-region complexes; the dissipation and changes in structure of older magnetic fields; the mutual interaction of all fields and their subsequent weakening as well as strenghtening; etc. All processes were found to be time antisymmetric; i. e., the growth phase was about 6 times longer than the declining phase. Similarly, the rapid final phase was accompanied by numerous flares and CMEs. Simultaneously, the entire area of complicated magnetic field patterns on the Sun, which at the phase of peak activity occupied as much as half of the solar surface, also disintegrated during this declining phase.

The persistence in the same longitude interval of the activity complex described in this paper suggests it was anchored to a rigidly rotating subsurface source of magnetic flux, which was not affected by the differential rotation, and which operated with maximum power through much of the complex's final phase. However, we have also noted significant changes in the local (possible local strenghtening of magnetic flux due to the strong motions, Bumba et al. 1995a, 1996) and large-scale magnetic topology that occurred during this period. At some point during this final period of maximum activity, the complex seems to become disconnected with this subsurface source, or the source itself has changed.

The evolution of this activity complex also parallels the evolution of large-scale magnetic fields studied during 1991 and 1992 (Bumba et al. 1995b). In both cases the disintegration of a large-scale magnetic complex led to the formation of a magnetically open region over the areas of formerly strong activity. In both cases, a large polar coronal hole penetrated into the area of the former activity complex and replaced it. From this we conclude that the development of a large coronal hole is a global process depending on the evolution of the global magnetic field. In addition, the evidence of this current study for the rigid rotation of magnetic boundaries of active-region complexes during the final stages of their evolution suggests "preparation" of the rigid boundaries of large coronal holes that penetrate low latitudes in the declining phase of the solar cycle. A well known example of this rigid rotation is the "boot of Italy" coronal hole observed by Skylab during 1973 (Krieger 1977). It should also be noted that the rigidly rotating pivot lines and pivot points discussed here appear to be associated with emerging flux regions and with the strengthening of this flux by other processes (Bumba et al. 1995a, 1996).

That substantial emerging flux may be needed during and immediately following the phase of peak activity and strong flaring, etc., is suggested by a recent study by Sudan & Spicer (1996). On the grounds of energetics and magnetodynamic stability, these authors argue that the energy for large flares must be emerging magnetic flux from subsurface regions, not magnetic energy stored in situ in the solar atmosphere. From this viewpoint, flares and other energetic manifestations of solar activity are mainly governed by the large-scale subsurface processes that determine magnetic flux generation and emergence, not by more local effects in the atmosphere itself. In further support of this picture, a possible driver for the "swelling" of helmet streamers often observed to precede CME eruptions could be the emergence of new magnetic flux from the subsurface regions (Hu, 1990), where similar energetic problems have been encountered (Low, 1993).

We also note there is evidence that the final opening into interplanetery space of the magnetic field lines in the region studied occurred well before its disconnection from a source of new flux, and even before the energetic event that announced the peak phase of activity, the flare and CME of July 9, 1982. This evidence is the difference between the weak radio emission recorded in June, 1989 from active region NOAA 3776 and the stronger, more typical radio emission from NOAA 3763 that was recorded earlier. Noting this, Bumba & Klvaňa (1997) report a corresponding change from a typically complex to a "twice bipolar" topological relationship between the magnetic fields of the activity complex and the global magnetic field, with the earlier case producing much more radio emission than the later, more dipole-like field.

At the end of the two-month period of peak activity in September 1982, the boundary of the large-scale region of positive magnetic field (the east edge of the leading portion of the global magnetic-bipolar structure) shifts eastward simultaneously with the simplification of the local magnetic field, "swallowing" the rest of the field into itself as it does so. This boundary is itself progressively transformed into, while merging with, the border of an expanding coronal hole, which started to grow earlier at higher latitudes, and continued to grow slowly to encompass lower latitude areas.

4. Summary

The activity complex studied here represents a basic structural element of the eleven year solar activity cycle. It occupied a substantial fraction of the solar surface. Its evolution exhibited a progressive increase in the number and size of its active regions, reaching a phase of peak activity during two rotations in June and July 1982. After this the magnetic field became greatly simplified over this entire area, with the lines of force opening into the interplanetary space, forming in its final stages a large coronal hole.

From the identification of pivot lines and pivot points for the rotation of the main boundary of the activity complex, we conclude that its subphotospheric source of magnetic flux rotated as a rigid body for at least four rotations prior to the phase of maximum activity. During this final most energetic phase, either the connection with the underlying source of flux had been severed, or the source itself had changed. On energetic grounds, a considerable emergence of new flux probably took place during the numerous strong flares that occurred within the complex before its destruction.

The complete "lifecycle" of this activity complex underscores the fundamental importance of large-scale subsurface processes for the generation, emergence, transformation and dissipation of the global magnetic field. It offers further insight into the relative rates at which activity builds up and then rapidly dissipates. Since a similar lifecycle was observed in detail during the following cycle, an anologous development of stellar activity complexes might be expected, given similar temporal and spatial organization of activity on other solar-like stars.

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References

Bumba V. 1982, Space Sci. Reviews 32, 229
Bumba V., Hejna L. 1987, Bull Astron. Inst. Czechosl. 38, 29

Bumba V., Klvaňa M. 1997, accepted in Solar Phys.
Bumba V., Klvaňa M., Kálmán B. 1995a, A&AS 109, 355
Bumba V., Klvaňa M., Kálmán B. 1996, A&AS 118, 35
Bumba V., Klvaňa M., Sýkora J. 1995b, A&AS 298, 923
Bumba V., Sýkora J. 1974, Coronal Disturbances, G. Newkirk, Jr. (ed.), Reidel Publ. Comp., Dordrecht, 73
Hu Y. -Q. 1990, Chinese Journal of Space Science 10, 163
Jordan S., Garcia A., Bumba V. 1997, Solar Phys. 173, 359
Krieger A. S. 1977, in Coronal Holes and High Speed Wind Streams, Zirker J. B. (ed.), Colorado Associated Univ. Press, Boulder, 71
Low, B. C. 1993, Adv.Space Res. 13(9), 93
Mouradian Z., Martres M. J., Soru-Escaut J., Gesztelyi L. 1987, A&A 183, 129
Mouradian Z., Soru-Escaut I. 1990, Publ. Debrecen Obs. 7, 36
Solneshnye Dannye, 1982, Academy of Sci. of the USSR, Astronom. council and the Main Astronom. Observatory, Leningrad, Nos 3-12
Sudan R. N., Spicer D. S. 1996, Comments Plasma Phys. Controlled Fusion 17, No 2, 77

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