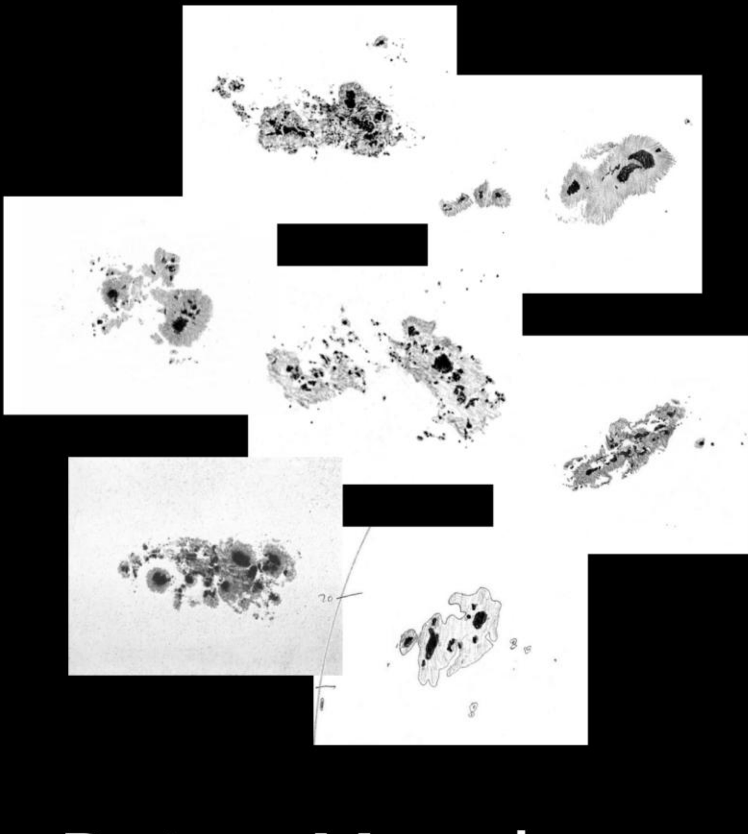
The Greatest Sunspot Groups



Peter Meadows

The Greatest Sunspot Groups

A description of the white light activity
of the largest sunspot groups

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Introduction

As with many areas of astronomy, it is the brightest or largest objects that are usually the most interesting and are observed by more astronomers. The same is true for the Sun, where large sunspots can be easily observed in white light provided safe observing practises are followed.

The largest recorded sunspot group occurred in April 1947 as shown in Figure 1. This an area of just over 6000 millionths of the Sun's visible hemisphere (MSH) or 0.6% of a hemisphere of the Sun. Remarkably, the five largest sunspots groups all occurred during a just over five-year period from February 1946 to May 1951. In addition, these are also the only groups with areas greater than 4500 MSH. Two other groups had areas greater than 4000 MSH – these being in 1989 and 2014 – as indicated in Table 1.

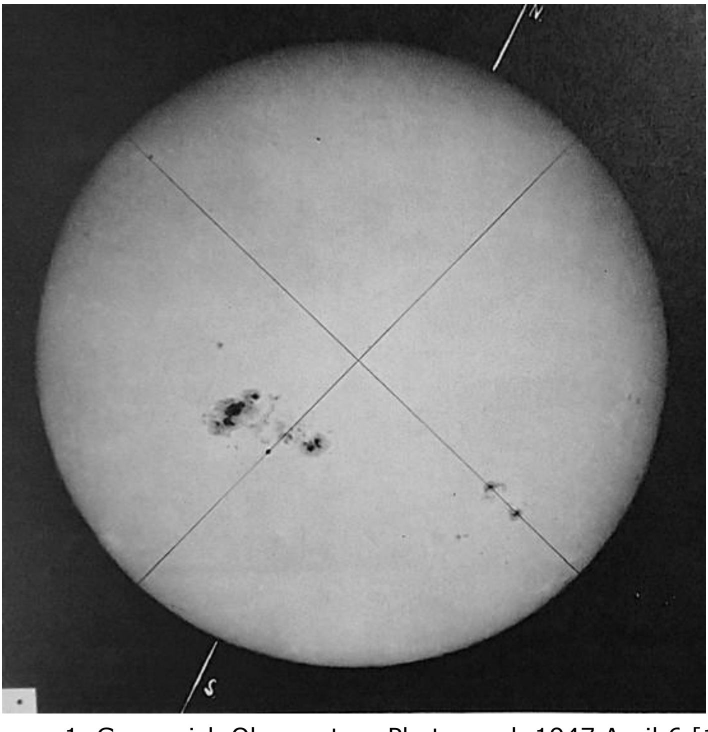


Figure 1. Greenwich Observatory Photograph 1947 April 6 [1]

Group	Date	Area (MSH)	Mean Lat.	Mean Long.
14886	1947 Apr 08	6132	-24.6°	82.7°
14417	1946 Feb 07	5202	26.3°	296.6°
16763	1951 May 19	4865	13.0°	86.2°
14585	1946 Jul 29	4720	22.4°	195.7°
14851	1947 Mar 12	4554	-23.1°	91.6°
12192	2014 Oct 24	4419	-13.7°	244.9°
5395	1989 Mar 14	4201	33.1°	256.1°

Table 1. Sunspot groups with maximum area greater than 4000 MSH [2]

This book will show the white light development of these seven great sunspot groups [6] in date order. In particular, the passage of these groups across the solar disk is described. Additionally, the main passage for all great groups with areas between 3000 and 4000 MSH are also shown. Finally, an area measurements is given for the sunspot group that Richard Carrington and Richard Hodgson independently observed one of the first white light solar flares on 1859 September 1. A total of 32 great sunspot groups are shown in this book.

Various sources of material have been used such solar drawings made at Mt Wilson Observatory, USA [8], by the Japanese solar observer Hisako Koyama [9], [10] and at the Specola Solare Ticinese, Locarno, Switzerland [11], reports and papers from the Journal of the British Astronomical Association (BAA), together with other material belonging to the author and available online. Various appendices describe in further detail some of the analysis performed for this book.

The orientation of most sunspot drawings and photographs has been chosen such that the Sun’s rotation axis in the vertical direction and east towards the right. This is the same orientation as the Mt Wilson & Locarno sunspot drawings and after a rotation for the position angle of the north point of the Sun’s axis, the same orientation as the Hisako Koyama sunspot drawings. This orientation ensures that the drawing annotations are still legible. Exceptions are for Figure 1, Figure 53 & Figure 66 (east towards the left) and Figure 3 (north at the top).

Warning: never look at the Sun with the naked eye or with any optical instrument unless you are familiar with safe solar observing methods.

February 1946 (Greenwich Group 14417)

This great sunspot group appeared around the eastern limb on 1946 January 29 as a single irregularly shaped penumbral sunspot at a heliographic latitude of 26°N. As Figure 2 illustrates, based on Mt Wilson drawings (Appendix D) and photograph, by the next day a following penumbral sunspot appeared on the limb. When the follower sunspot had fully rotated onto the disk on January 31 the bipolar nature of this group could be seen with the follower being the largest sunspot. Several umbrae were present within the two main penumbral sunspots. On February 1, the group had an area of 4799 MSH (based on Greenwich sunspot group data [3]). As the group neared the central meridian, a few small penumbral sunspots and pores appeared between the two main sunspots and at the following (east) part of the group. The main umbra of the following sunspot had separated into two between February 2 and 5. The leader sunspot had split by February 6 although it appeared as one penumbral sunspot again by February 8. The group obtained its maximum area of 5202 MSH on February 7 (see Table 2) when it also obtained its maximum longitude extent of 27° (330,000 km). The leader had decayed by February 9 and rotated off the disk on February 10. The follower remained on the disk for a further two days with it last seen as a very slender sunspot near the limb on February 12 – its latitude extent remained undiminished.

Greenwich Group Number	Mt Wilson Number	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
14417	**7943**	**1946 Jan 29**	**1946 Feb 12**	**26.3°**	**294.8°**	**5202**	**1946 Feb 07**
14451	7978	1946 Feb 28	1946 Mar 12	28.0°	276.0°	1741	1946 Mar 04
14478	8006	1946 Mar 29	1946 Apr 09	26.8°	259.6°	768	1946 Apr 02

Table 2. Information on Group 14417 and subsequent rotations

Note that for Figure 2 and similar figures in this book, the sub-image scale of drawings and photographs are all the same - approximately 30° in longitude by 23° in latitude when near the central meridian. The drawing orientation is shown in the bottom right of each figure (rotation axis being vertical and east to the right). The Mt Wilson drawings were typically drawn at a local time of 10 hrs or 18 hrs UT. Figure 2 also shows differences in drawing styles and detail between Mt Wilson observers.

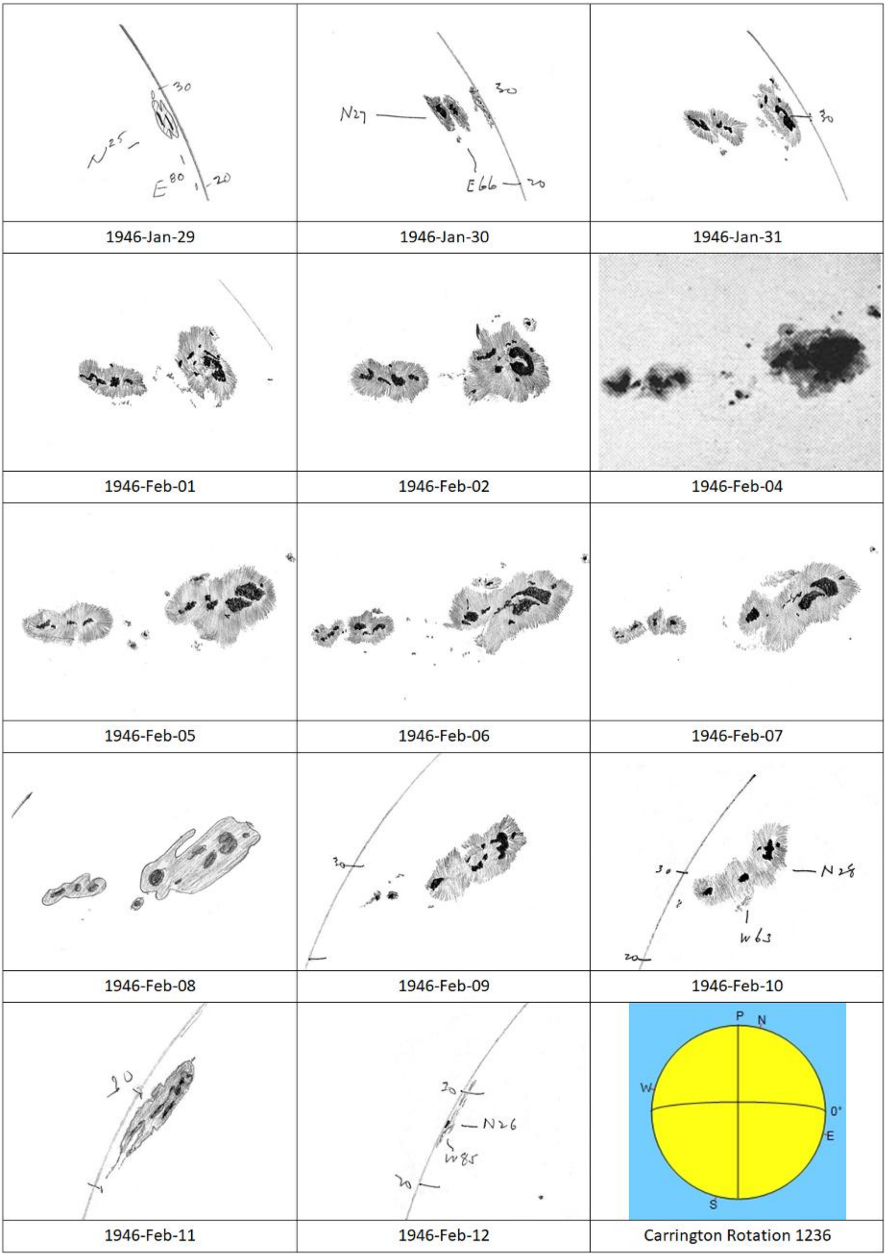


Figure 2. Passage of Greenwich Group 14417 based on Mt Wilson Drawings and Photograph [12]

Figure 3 shows drawings of the passage of group 14417 by BAA member Dr M.A. Ellison using a disk diameter of 11 inch [13][14] – these show similar or in some cases more detail than the Mt Wilson drawings.

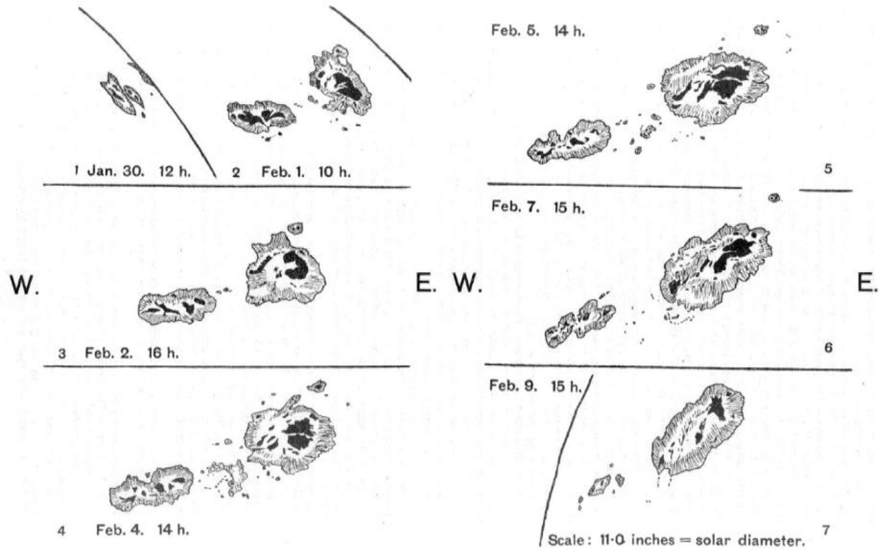


Figure 3. Drawings of the Great Sunspot of 1946 February by Dr M.A. Ellison [13][14]

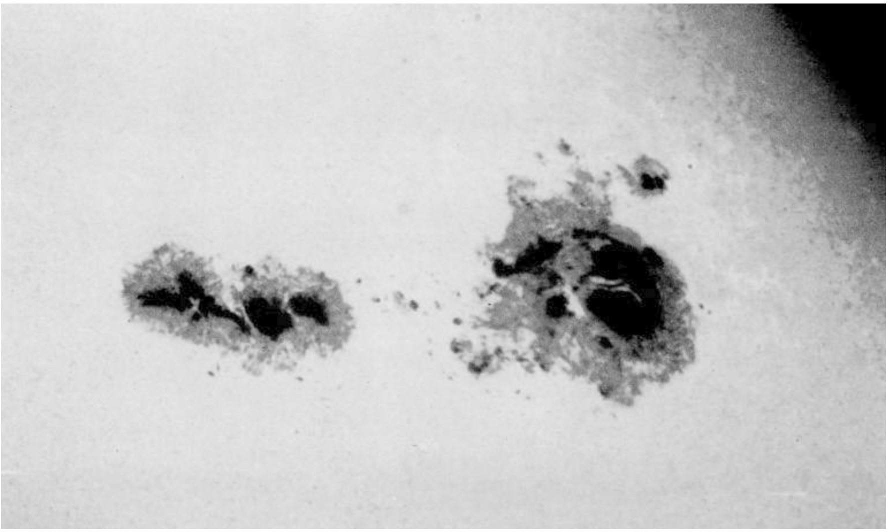


Figure 4. Mt Wilson Photograph on 1946 February 2 [15]

As Table 2 indicates, the great sunspot returned on two subsequent rotations as Greenwich group numbers 14451 and 14478 albeit at reduced areas. Figure 5 shows the passage for the second rotation (every other day) – the largest sunspot was still the follower with a maximum area on March 4 of 1741 MSH and a longitude extent of 31° (376,000 km). As the group progressed towards the western limb, all the leader sunspots decayed such that on March 11 the area was just 850 MSH and a much reduced longitude extent of just 7°. A single small penumbral sunspot was close to the western limb on March 12.

On the third rotation, Figure 6, the group was much diminished and without any particular structure – it appeared as a collection of small penumbral sunspots and pores. Its total area was a maximum for this rotation on April 2 at 768 MSH (the group would have still been visible with the protected naked eye). On this date the longitude extent of the group was 11°.

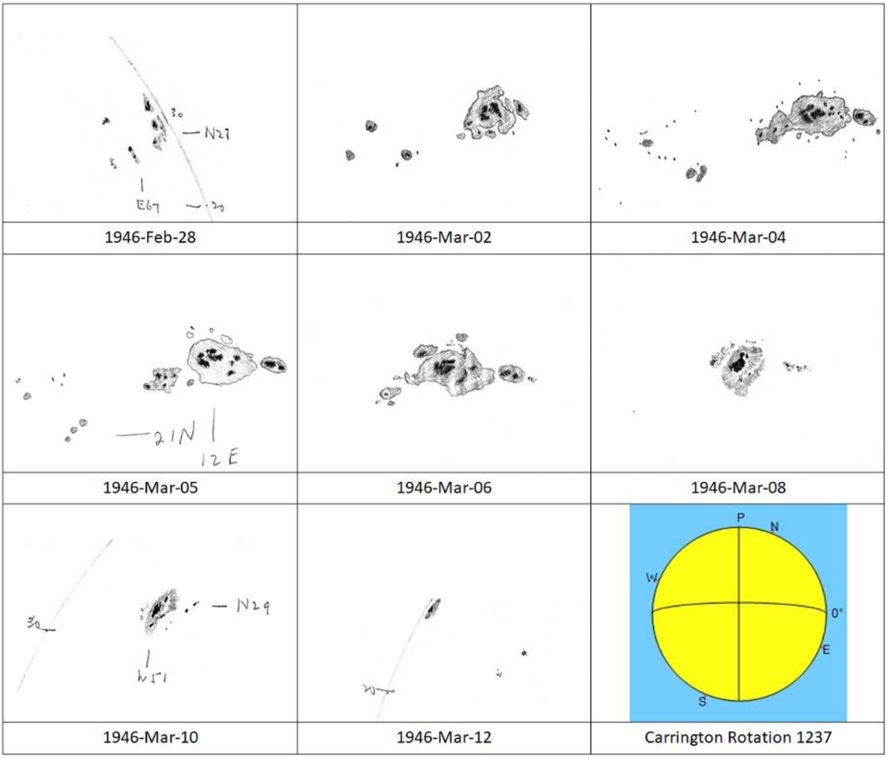


Figure 5. Passage of Greenwich Group 14451 based on Mt Wilson Drawings

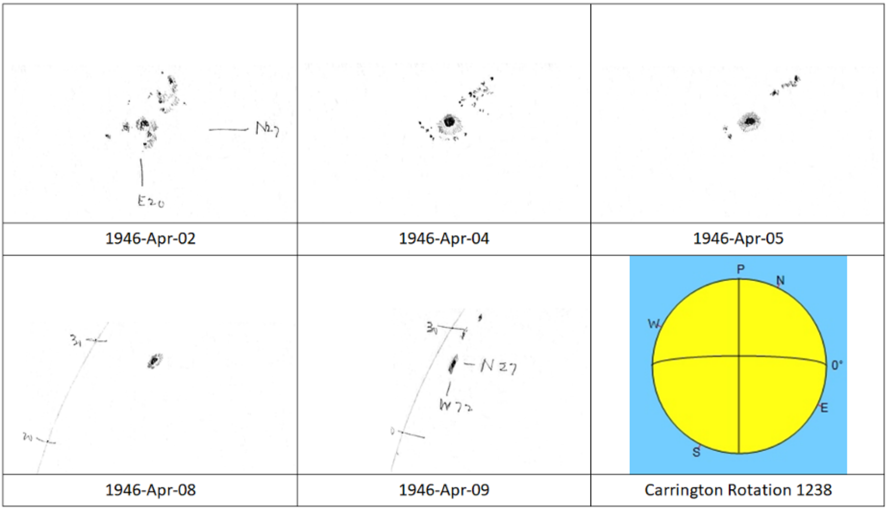


Figure 6. Passage of Greenwich Group 14478 based on Mt Wilson Drawings

Figure 7 shows the evolution of group area for the three rotations (area plotted against central meridian distance with east being negative and hence time increases left to right).

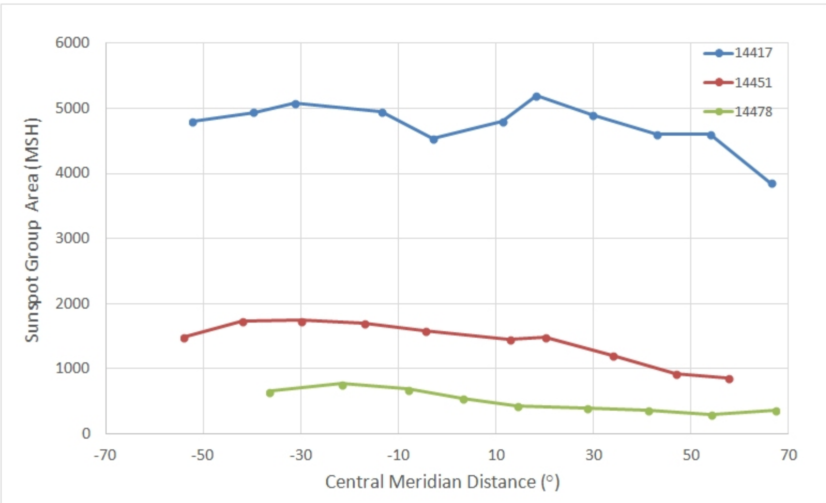


Figure 7. Greenwich sunspot area for Groups 14417, 14451 and 14478 (1946 January to April)

July 1946 (Greenwich Group 14585)

A few months after the first great sunspot group of Cycle 18, the second great group appeared around the eastern limb on 1946 July 19 as shown in Figure 8 with details given in Table 3. By the following day it became clear that this group, at latitude 22°N, would be a large complex single penumbral sunspot. As the sunspot progressed towards the central meridian, more individual penumbral sunspots appeared to break away from the original single penumbral sunspot. As shown in Figure 9 on July 25 there were many nearby penumbral sunspots throughout the group (the N and S indicate the north and south magnetic fields as determined at Mt Wilson). Changes within the penumbra and the size and position of umbrae occurred from day to day. Figure 10 shows the group on July 27 by BAA Member Mr E.J. Harris using an 8in refractor (stopped down to 1.5in) at Temple Observatory, Rugby, England [16]. The group obtained its maximum area of 4720 MSH on July 29 as it neared the western limb when its longitudinal extent was 18° (223,000 km). The group appeared to break apart on July 31 and it was last seen on August 2 as a slender leader with two smaller followers.

This group reappeared on August 17 as group 14620 with a much-reduced size and with the follower being the larger sunspot. Figure 11 shows the passage of the group – there was the development of a number of the leading penumbral sunspots and the splitting of the follower into two parts. Greenwich data indicates that the maximum area was obtained on August 20 (Table 3) at 988 MSH (an easy protected naked eye group). On August 24, a maximum longitudinal extent was obtained of 23°. As the group neared the western limb, the number and size of sunspots within the group diminished.

Figure 12 shows the change in the group area for both rotations – there was some daily variation for the first rotation while there was a steady decrease for the second rotation.

Greenwich Group Number	Mt Wilson Number	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
14585	**8129**	**1946 Jul 19**	**1946 Aug 02**	**22.1°**	**197.0°**	**4720**	**1946 Jul 29**
14620	8163	1946 Aug 17	1946 Aug 30	23.3°	182.1°	988	1946 Aug 20

Table 3. Information on Group 14585 and subsequent rotation

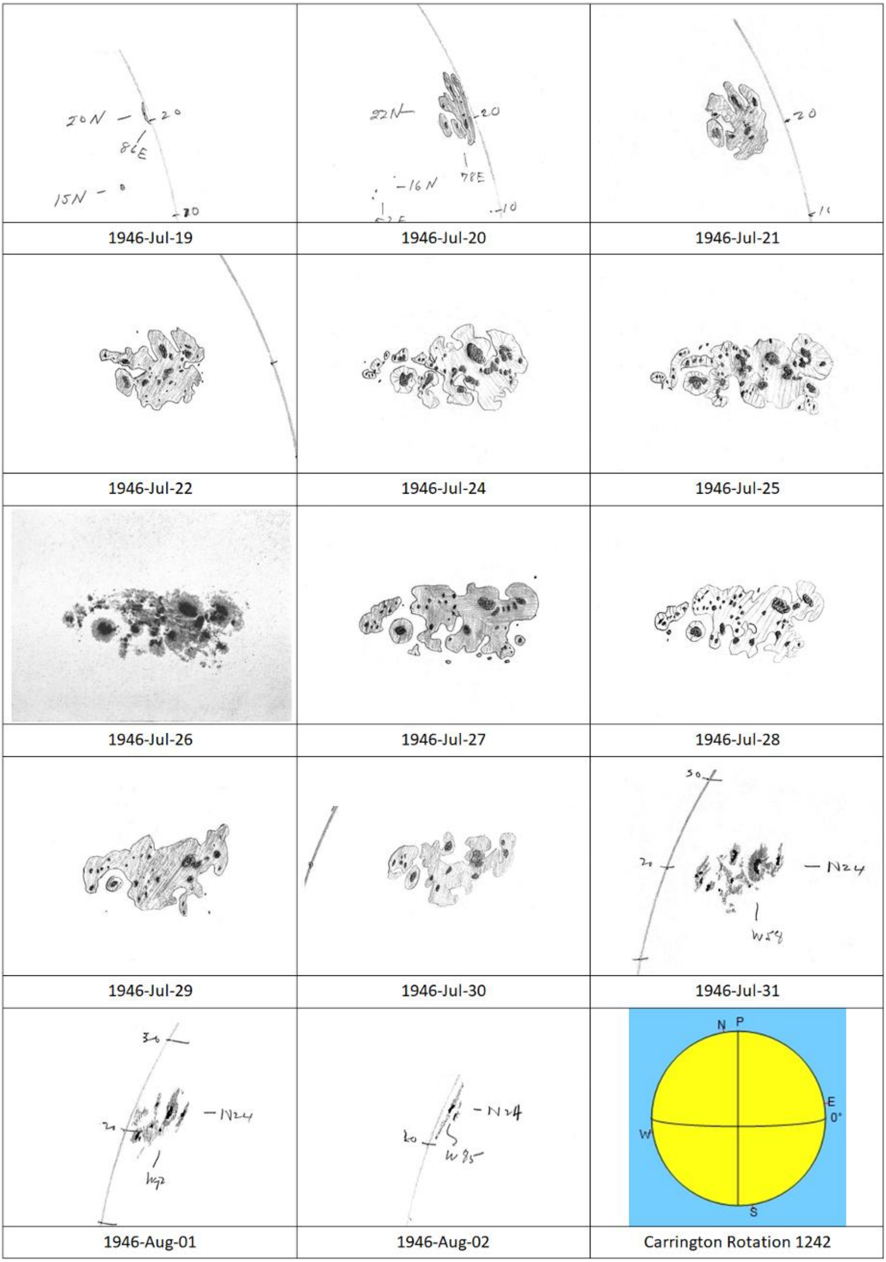


Figure 8. Passage of Greenwich Group 14585 based on Mt Wilson Drawings and Photograph [17]

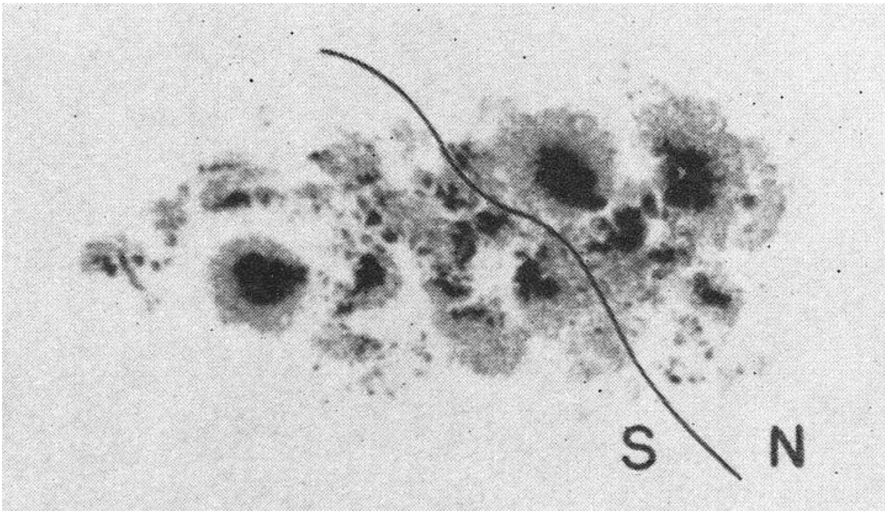


Figure 9. Mt Wilson Photograph on 1946 July 25 [18]

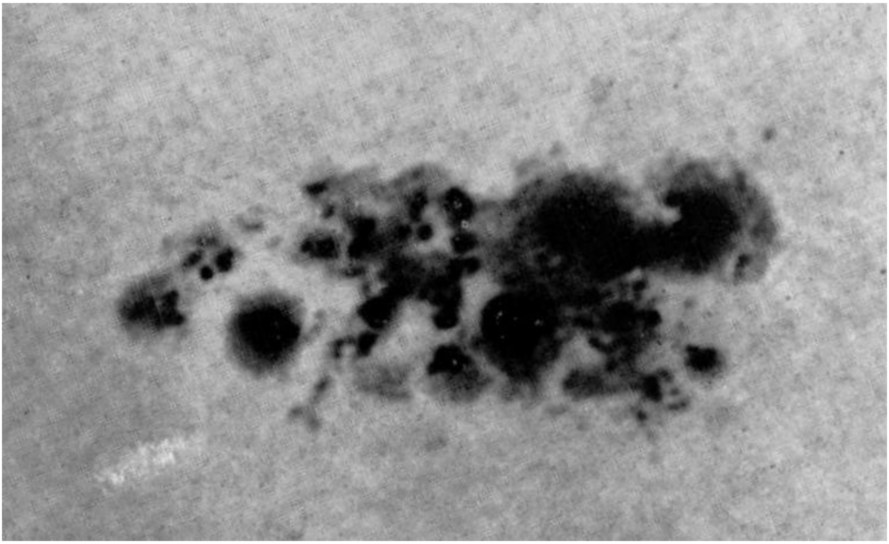


Figure 10. Group 14585 on 1946 July 27 by BAA Member Mr E.J. Harris [16]

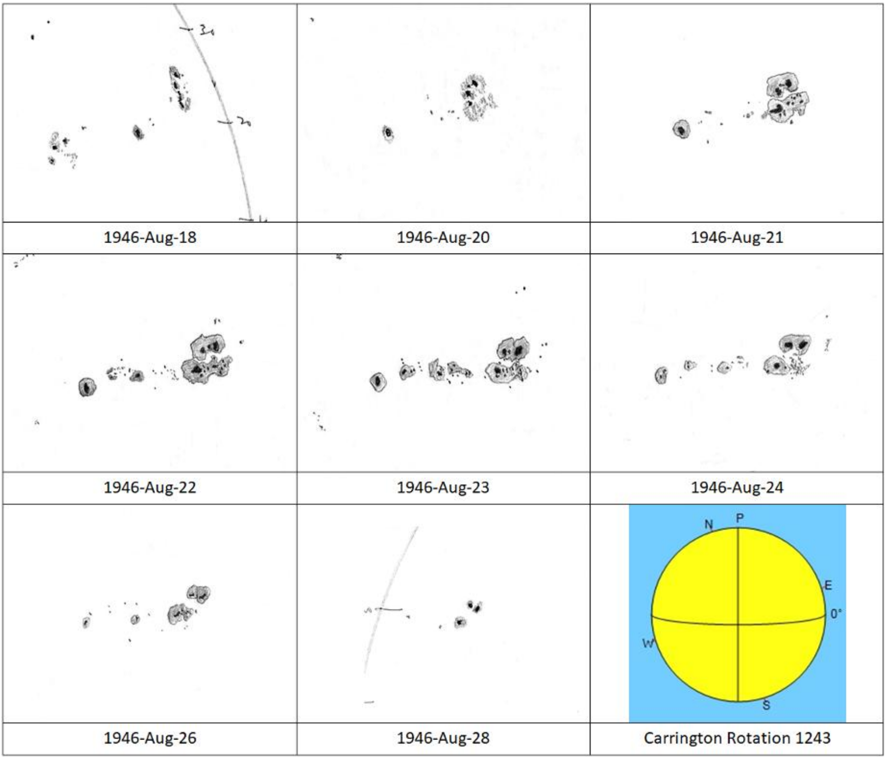


Figure 11. Passage of Greenwich Group 14620 based on Mt Wilson Drawings

Tables 2 and 3 include the mean latitude and longitude of the group based on Greenwich data. It can be seen that there is a longitude drift from rotation to rotation. This is expected as the longitude is based on a fixed rotation rate whereas differential rotation occurs for a gaseous body such as the Sun. Figure 13 shows the evolution of the longitude extent of the two 1946 great groups and their subsequent rotations. The blue diamonds are for the longitude of the largest sunspot while the green lines indicate the longitudinal extent of the group. These have been derived using full disk Mt Wilson drawings (Appendix D) and Helio Viewer software [19] to measure the various longitudes. It is clear that there is a constant drift for all of the five rotations. This was pointed out at the time [20] with the conclusion that the two 1946 great sunspot groups were actually from the same region of the photosphere. Appendix F and Figure 79 show that the mean reduction in longitude per synodic rotation (i.e. as seen from Earth) is 15.3° (based on the mean longitude of the largest sunspot within the group for all five rotations as shown by the black line in Figure 13). This is significantly higher than would be indicated by differential rotation alone, indicating at least a 7°

proper motion per rotation (depending on the differential rotation model – see Appendix F).

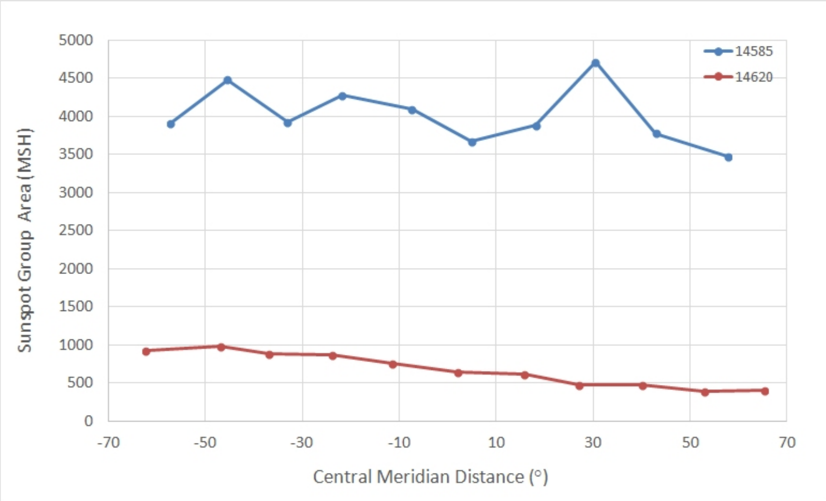


Figure 12. Greenwich sunspot area for Groups 14585 and 14620 (1946 July and August)

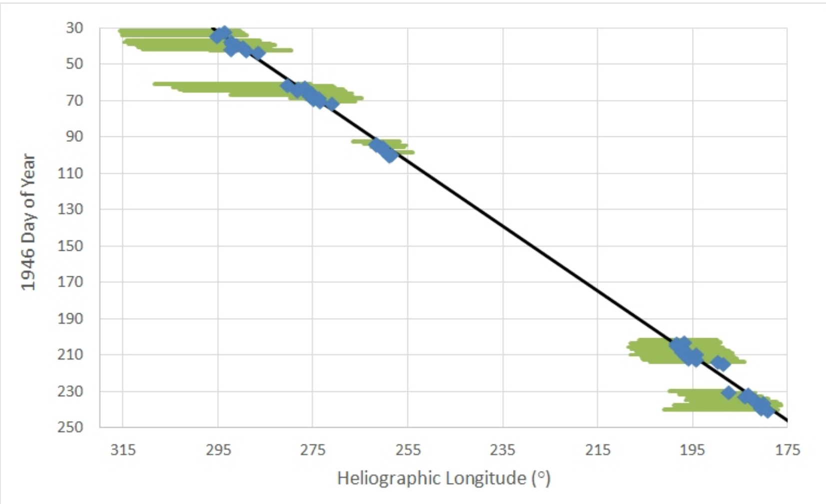


Figure 13. Longitude evolution of Groups 14417, 14585 and subsequent rotations

March 1947 (Greenwich Group 14851)

On 1947 February 6 a small collection of sunspots were seen close to the eastern limb at a latitude of 21°S (Group 14813). As shown in Figure 14, based on Mt Wilson and Hisako Koyama (Appendix E) disk drawings, this group developed rapidly with several following penumbral sunspots appearing by February 8 and throughout the whole group by February 10 when it had its maximum area of 2944 MSH (Table 4). It reached the central meridian on February 11. The area of the group changed little as it neared the western limb - it had an area of 2938 MSH on February 15 when it had a longitudinal extent of 23° (283,000 km). This group rotated off the disk three days later as a single slender penumbral sunspot.

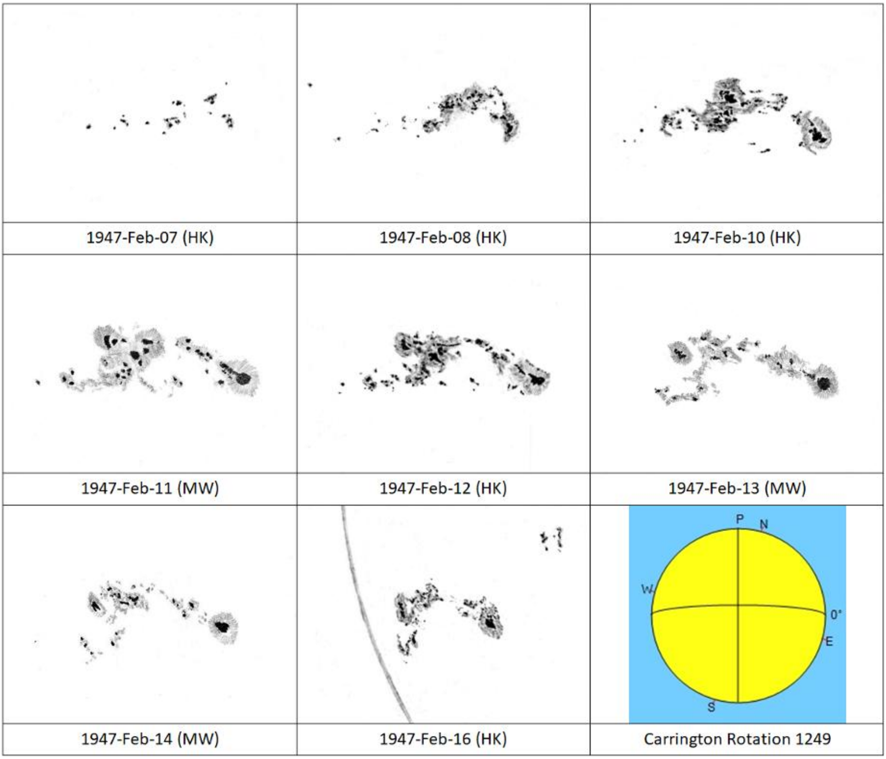


Figure 14. Passage of Greenwich Group 14813 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

Greenwich Group Number	MW	HK	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
14813	8392	18	1947 Feb 05	1947 Feb 18	-21.2°	84.9°	2938	1947 Feb 10
14851	**8438**	**40**	**1947 Mar 03**	**1947 Mar 16**	**-23.3°**	**91.2°**	**4554**	**1947 Mar 12**

Table 4. Information on Group 14851 and previous rotation

On the next rotation two penumbral sunspots appeared near to the eastern limb on March 3 at a similar latitude and longitude as on the previous rotation. When this group, 14851, had rotated further onto the disk (Figure 16 and Figure 17) it primarily consisted of three nearby penumbral sunspots with the southern two sunspots being quite irregularly shaped. On March 5, the total area was already 2579 MSH. Over subsequent days, the penumbral sunspots appeared to merge and extend in longitude (sunspots to the north-east and north-west were from other groups). Some regions of photosphere were seen within the main sunspot, especially when the group was in the western hemisphere. Figure 15 shows Group 14851 when it was just before the central meridian on March 9. The group has an area of just over 4500 MSH on March 11 and 12 before reducing in size slightly as it neared the western limb although its longitudinal extent was just over 20° (246,000 km). Throughout its passage, Group 14851 had many umbrae within the main sunspot and pores around it. On March 16, the group appeared as a highly elongated sunspot close to the western limb.

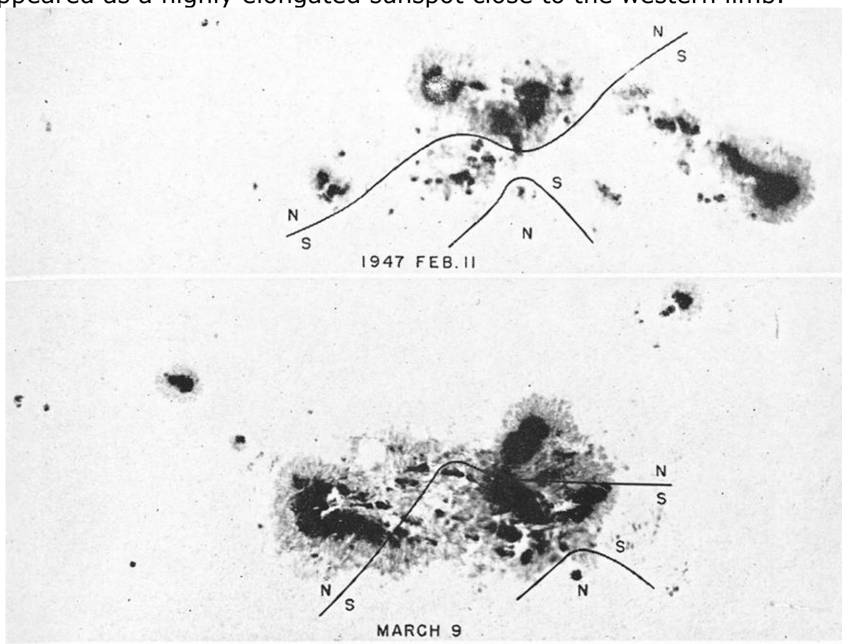


Figure 15. Mt Wilson Photographs of Groups 14813 and 14851 [21]

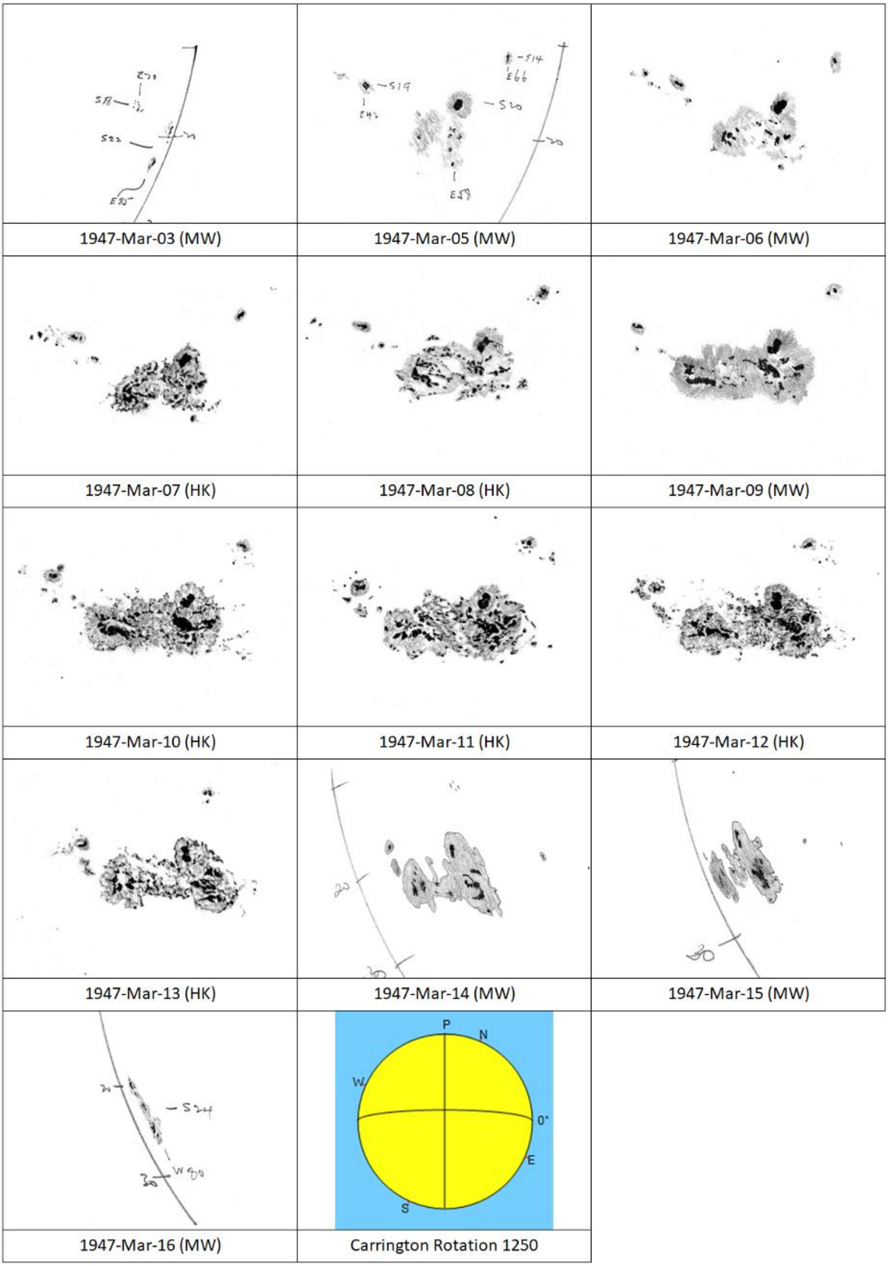


Figure 16. Passage of Greenwich Group 14851 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

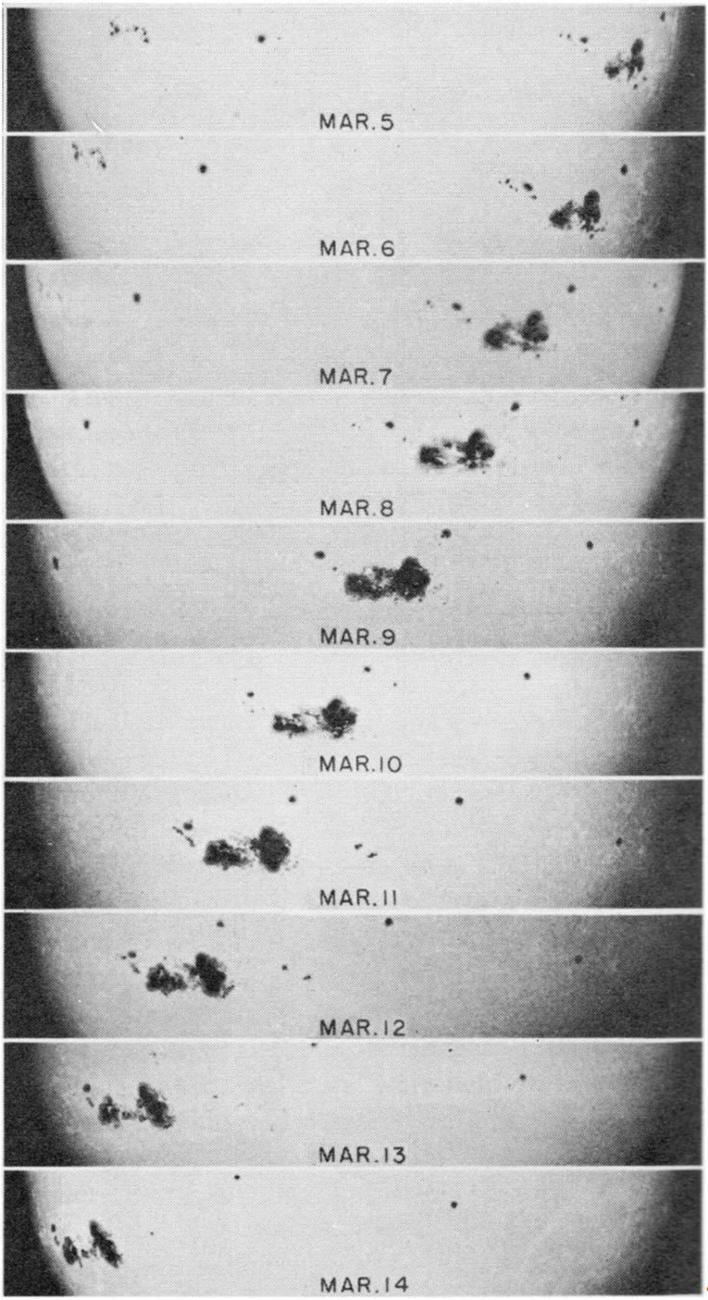


Figure 17. Passage of Greenwich Group 14851 based on Mt Wilson Photographs [22]

April 1947 (Greenwich Group 14886)

Group 14851 from 1947 March reappeared around the limb on March 30 as a single penumbral sunspot (Figure 19 and Figure 21) – this was the start of the passage of the largest recorded sunspot group. By the following day, a much larger irregularly shaped sunspot had appeared around the limb. The complete group, 14886, was not on the disk until April 1 when it had already had an area of 5400 MSH. The group was quite irregular with regions of photosphere seen between the leader and follower penumbral sunspots. Many umbrae were present throughout the group as were a small number of pores. The central portion of the group changed the most as it crossed the central meridian on April 7 (Figure 18 and Figure 20). It obtained its maximum area of 6132 MSH on April 8 with a longitudinal extent of 25° (300,000 km). As the group progressed towards the western limb, the leading penumbral sunspot reduced in size to leave a few small leaders and a large irregular following penumbral sunspot on April 13 (3617 MSH). The group was last seen on April 14 (Table 5).

Greenwich Group Number	MW	HK	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
14886	**8478**	**59**	**1947 Mar 30**	**1947 Apr 14**	**-24.5°**	**81.9°**	**6132**	**1947 Apr 08**
14933	8527	86	1947 Apr 29	1947 May 11	-24.8°	67.7°	782	1947 May 01

Table 5. Information on Group 14886 and subsequent rotation

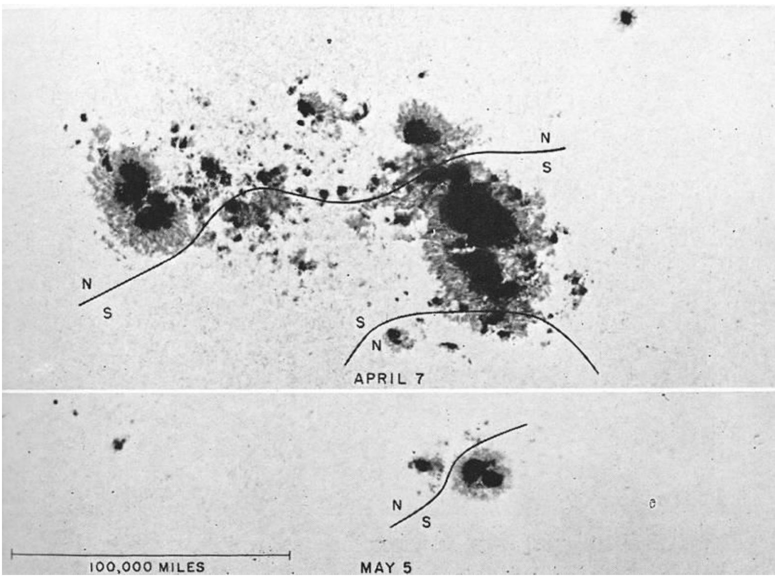


Figure 18. Mt Wilson Photographs of Groups 14886 and 14933 [21]

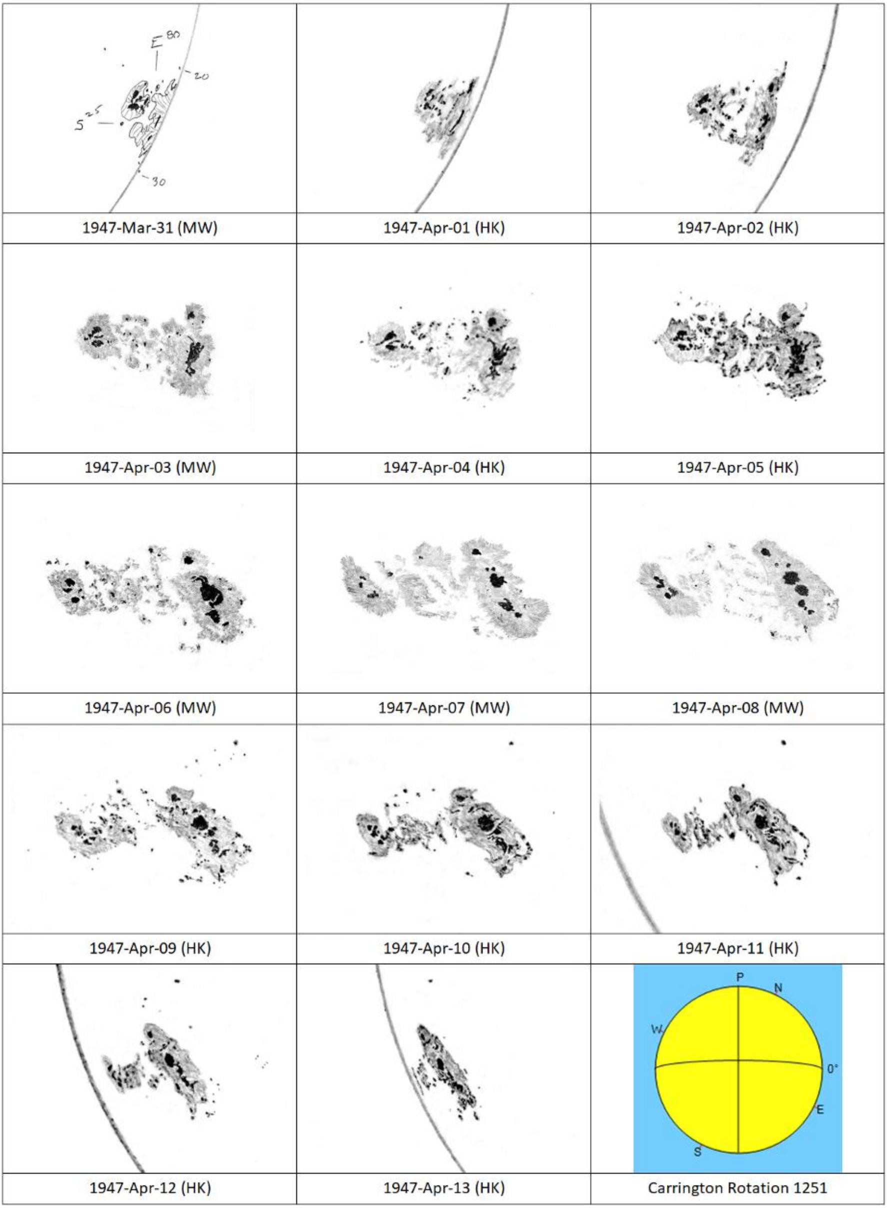


Figure 19. Passage of Greenwich Group 14886 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

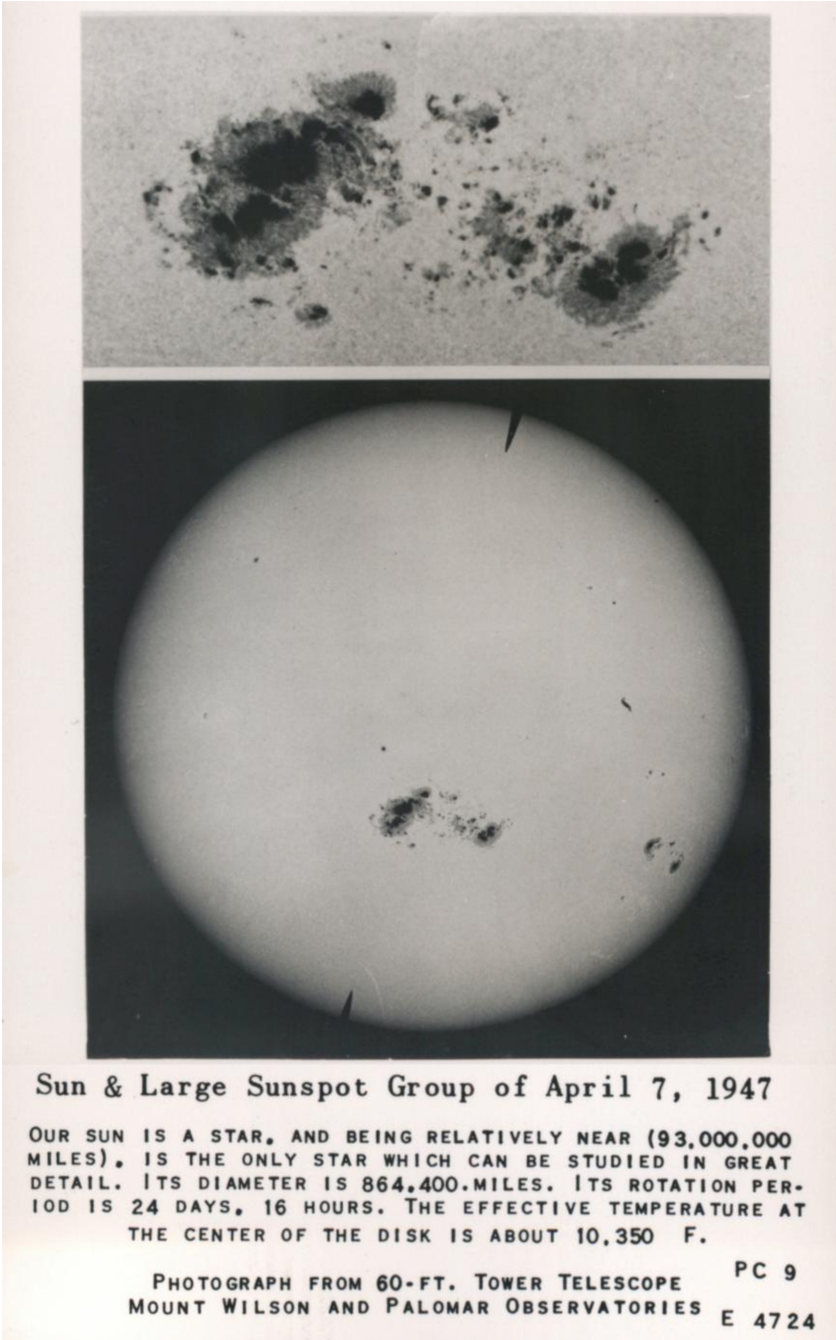


Figure 20. Mt Wilson Postcard

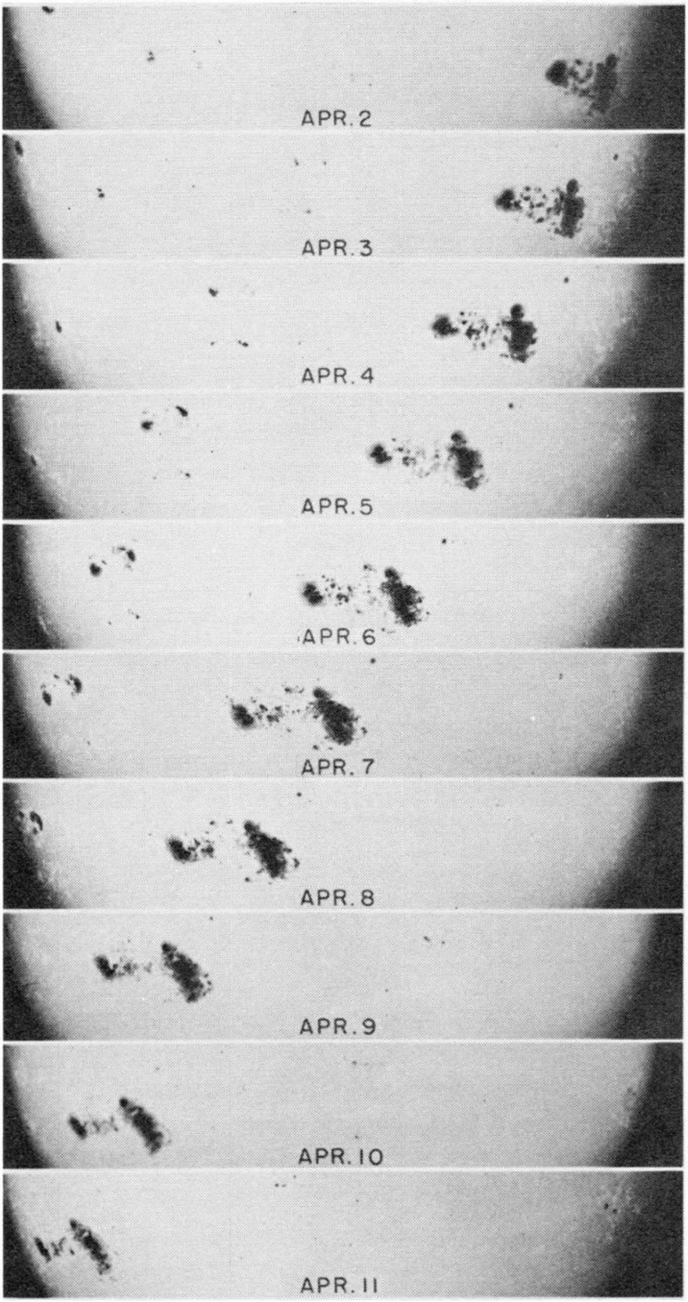


Figure 21. Passage of Greenwich Group 14886 based on Mt Wilson Photographs [22]

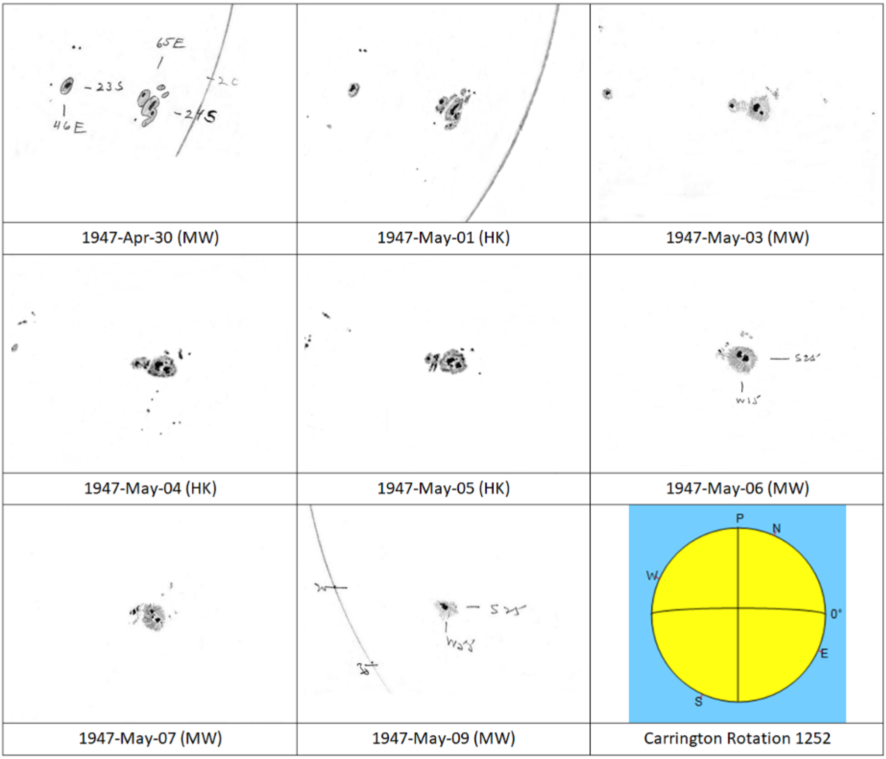


Figure 22. Passage of Greenwich Group 14933 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

On the fourth and last rotation, the greatest sunspot group had diminished significantly as shown in Figure 22 although it still obtained a maximum area of 782 MSH on May 1 (Table 5) and its longitudinal extent was almost unchanged at 21°. The evolution in sunspot area over the four rotations is shown in Figure 24.

The longitude evolution of the four 1947 rotations given in Tables 4 and 5 is shown in Figure 25. Based on the evolution of the largest sunspot (the black line), it can be seen that there is a difference between the first rotation (group 14813) and the other three rotations (groups 14851, 14886 and 14933). Projecting the black line back to the first group shows that only the leading part of group 14813 overlaps with other three subsequent rotations. This is illustrated in Figure 26 where the blue box shows the location of the region of photosphere that matches the subsequent rotations assuming same longitudinal drift as the last three rotations and a longitude extend of 20°. This includes only the leading part of group 14813 (Koyama group 18) but also Koyama group 20.

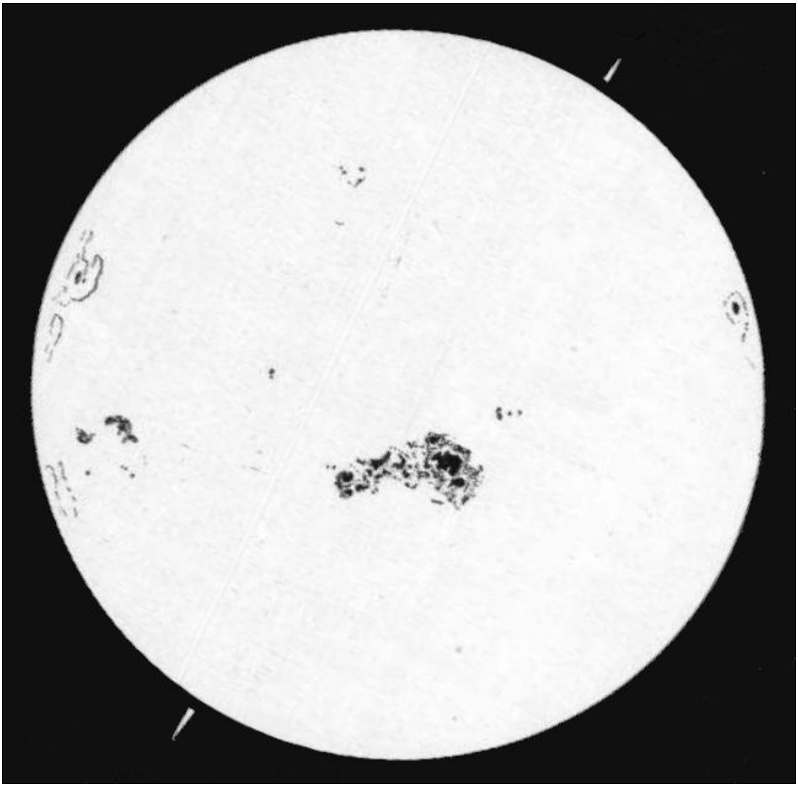


Figure 23. Group 14886 on 1947 April 6 by BAA Member Richard Baum [23]

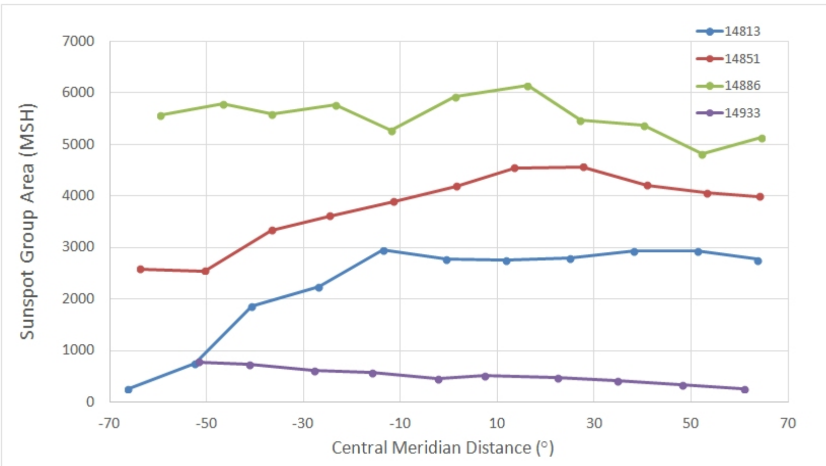


Figure 24. Greenwich sunspot area for Groups 14813, 14851, 14886 and 14933 (1947 February to May)

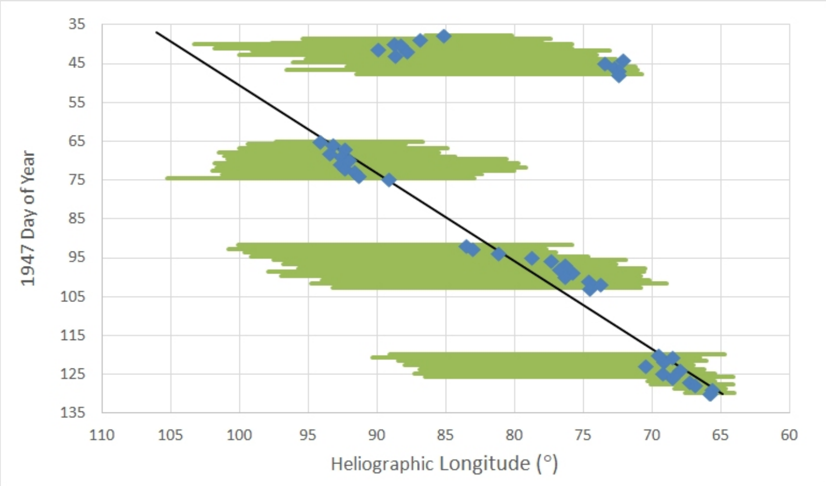


Figure 25. Longitude evolution of Groups 14851, 14886, previous and subsequent rotations.

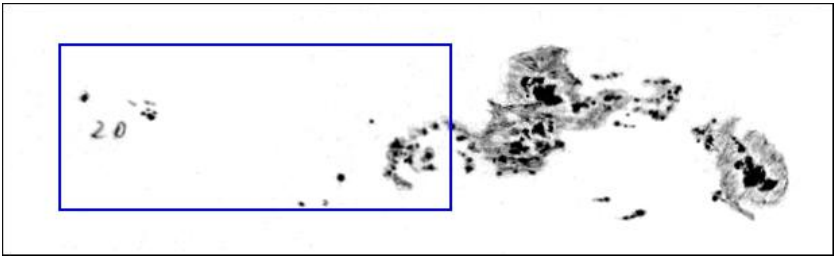


Figure 26. Expected location of Groups 14851 and 14886 on 1947 February 10 (Hisako Koyama drawing)

Figure 79 indicates a longitude drift of 12.1° per rotation based in the largest sunspot (also as shown in Figure 25) and 7.8° per rotation based on the mean longitude of the group. At a mean latitude of 24.5°S, the drift is close to the Maunder differential curve for the largest sunspot and 4° of proper motion per rotation based on the mean longitude (all based on the last three rotations).

May 1951 (Greenwich Group 16763)

On 1951 April 12 two irregularly shaped penumbral sunspots appeared around the eastern limb at latitude 12°N. As these rotated further on to the disk on Apr 14, as shown in Figure 27 it could be seen that this group was a moderately sized bipolar group with the follower being the more irregularly shaped sunspot – this was group 16745 (Table 6). As the group progressed towards the central meridian, the follower grew in size and included many umbrae and a few surrounding pores. This follower then appeared to decay into several parts – this group obtained its maximum area of 2553 MSH on April 19 when it had a longitude extent of 13° (155,000 km). As the group neared the western limb, only several small penumbral sunspots were seen – both the larger leader and follower sunspots had decayed.

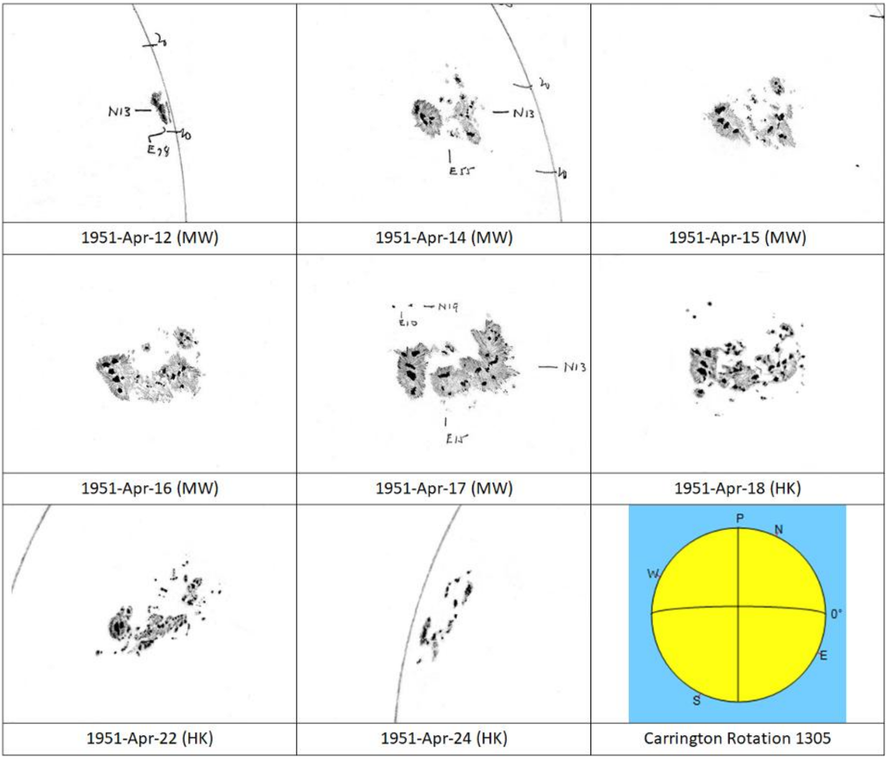


Figure 27. Passage of Greenwich Group 16745 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

GW	MW	HK	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
16745	10639	998	1951 Apr 12	1951 Apr 25	12.1°	87.9°	2553	1951 Apr 19
16763	**10662**	**1009**	**1951 May 09**	**1951 May 22**	**13.0°**	**86.8°**	**4865**	**1951 May 19**
16792	10690	1023	1951 Jun 05	1951 Jun 18	13.7°	89.0°	1354	1951 Jun 06

Table 6. Information on Group 16763, previous and subsequent rotations

On the next rotation, a single small penumbral sunspot appeared on the eastern limb on May 9 (group 16763) at latitude 13°N. By the next day, an irregular follower penumbral sunspot with a much larger latitude extent appeared. It was not until May 11 that the full extent of the group was seen and when it had an area of 2500 MSH. As shown in Figure 28, the following penumbral sunspot rapidly grew in size and which contained many large umbrae. On May 16, the group was near the central meridian and just over 4000 MSH and it had a longitudinal extent of 17°. Two other groups were seen to the east and south of the follower sunspots. A fine photograph of this group on May 17 is shown in Figure 28. As the group progressed towards the west it continued to grow, obtaining a maximum size of 4865 MSH on May 19. As it neared the western limb, the follower remained approximately of a similar shape and it was last seen on May 22 as a slender penumbral sunspot.

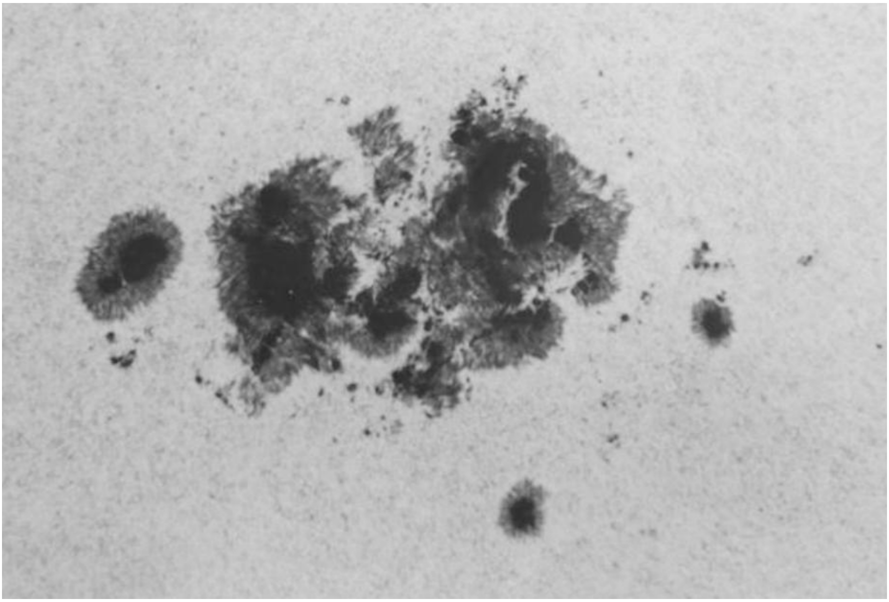


Figure 28. Mt Wilson Photograph on 1951 May 17 [24]

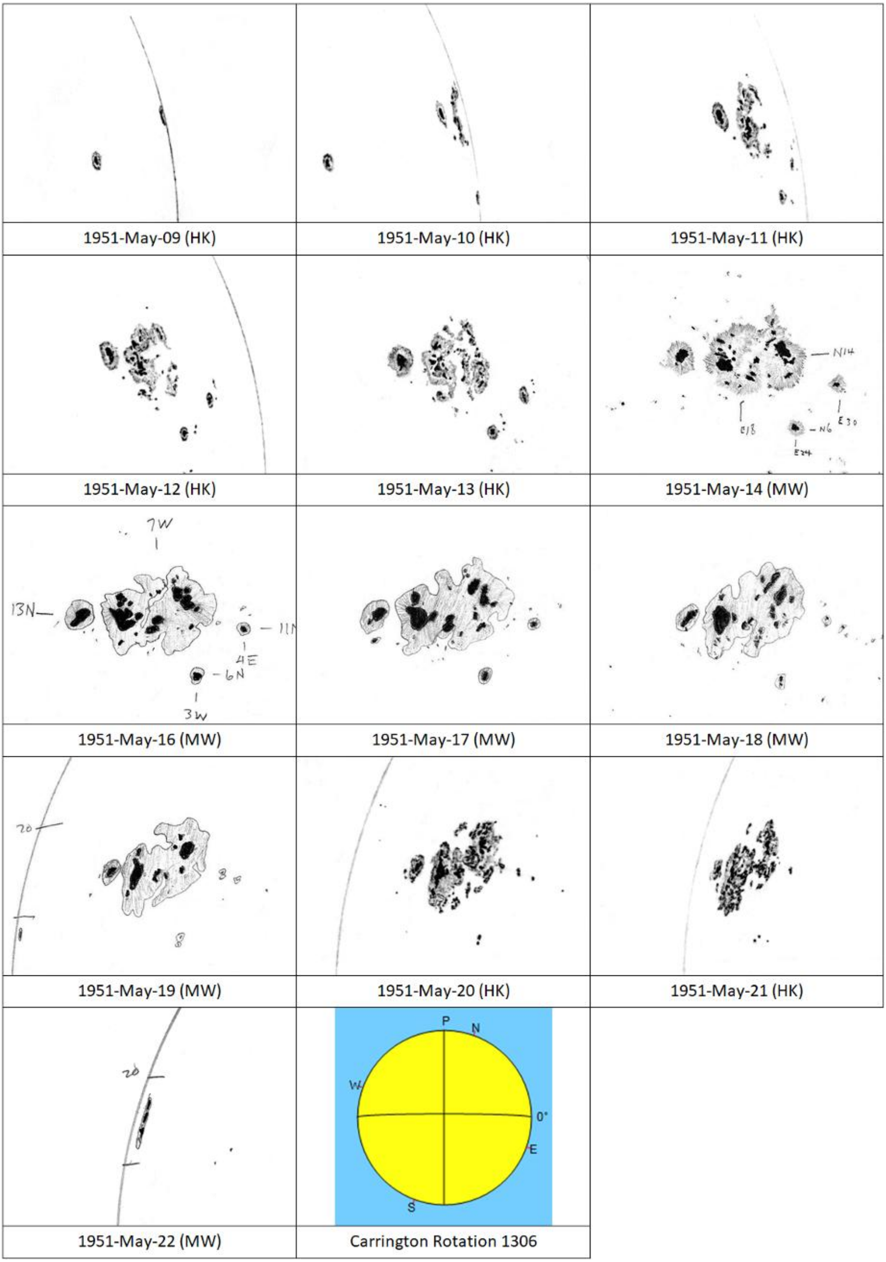


Figure 29. Passage of Greenwich Group 16763 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

On the third and final rotation, a collection of sunspots without any particular structure was seen – see Figure 30. The northern set of sunspots was the remains of the May great sunspot group, which must have decayed while on the averted disk. By the time this group, 16792, approached the western limb just a few small penumbral sunspots remained.

The area evolution of groups 16745, 16763 and 16792 is shown in Figure 31 while the longitude evolution over the three rotations is shown in Figure 32. For the largest sunspot (blue diamond's) there is no obvious longitude drift with time (unlike the great sunspots in 1946 and 1947) while for the longitude extent, the three rotations all give a similar longitude, i.e. there is very little drift in longitude. Indeed, Figure 79 shows that the expected change in rotation rate due to differential rotation is just 1.4° per rotation (for 13° latitude) for the Maunder rotation rates (i.e. the Carrington and Differential rotation rates are very similar).

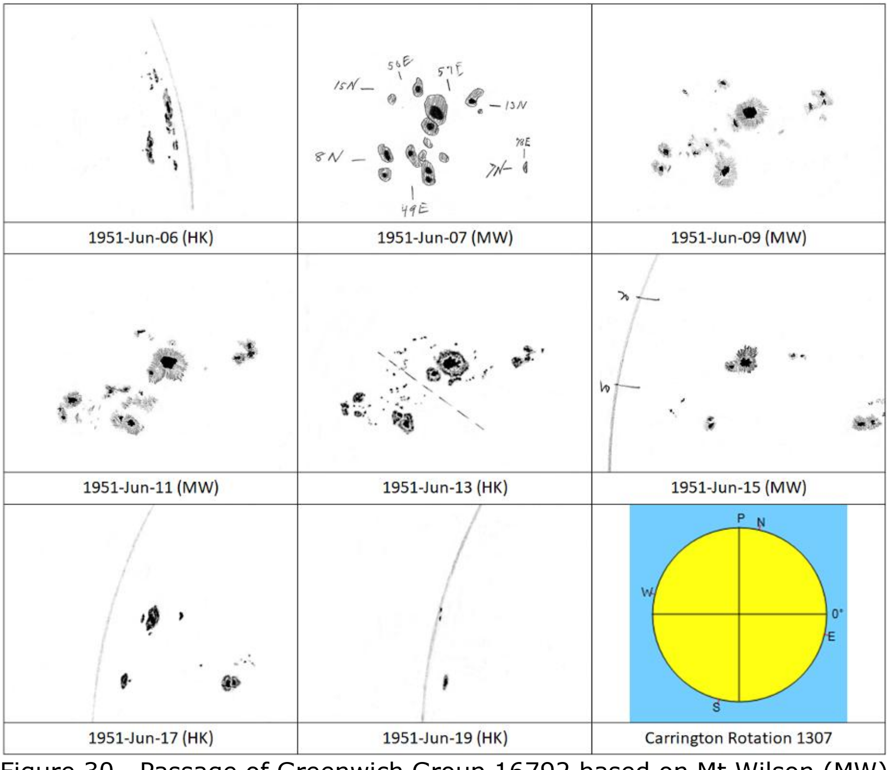


Figure 30. Passage of Greenwich Group 16792 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

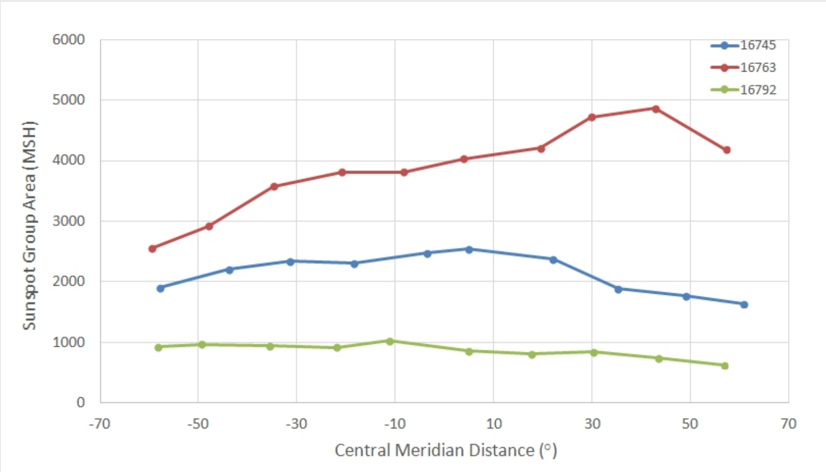


Figure 31. Greenwich sunspot area for Groups 16745, 16763 and 16792 (1951 April to June)

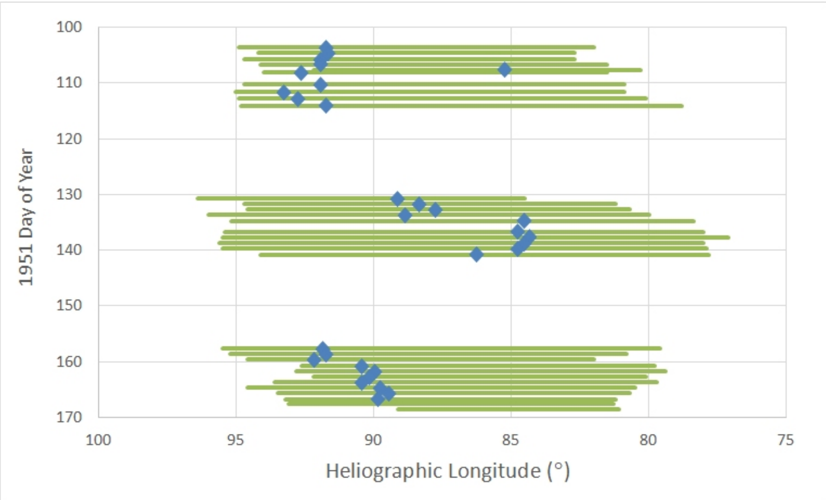


Figure 32. Longitude evolution of Groups 16763, previous and subsequent rotations

March 1989 (NOAA Active Region 5395)

The largest group recorded at a latitude of 30° above or below the solar equator appeared in early 1989 (Appendix J) at the start of the first maximum of cycle 22 (Appendix A). The group first appeared on 1989 February 5 as a complex bipolar group having just rotated around the eastern limb. Two days later it obtained it maximum area for this rotation of 2400 MSH which would have been easily visible to the protected naked eye. There were some changes in the appearance of the group as it progressed across the disk – see Figure 33 – the follower penumbral sunspot was the largest sunspot within the group. It reached a maximum longitudinal extent of 19° on February 12. The group approached the western limb on February 16 and with only the follower visible on the following day. Table 7 indicates that the mean latitude was 31.5°N for this rotation.

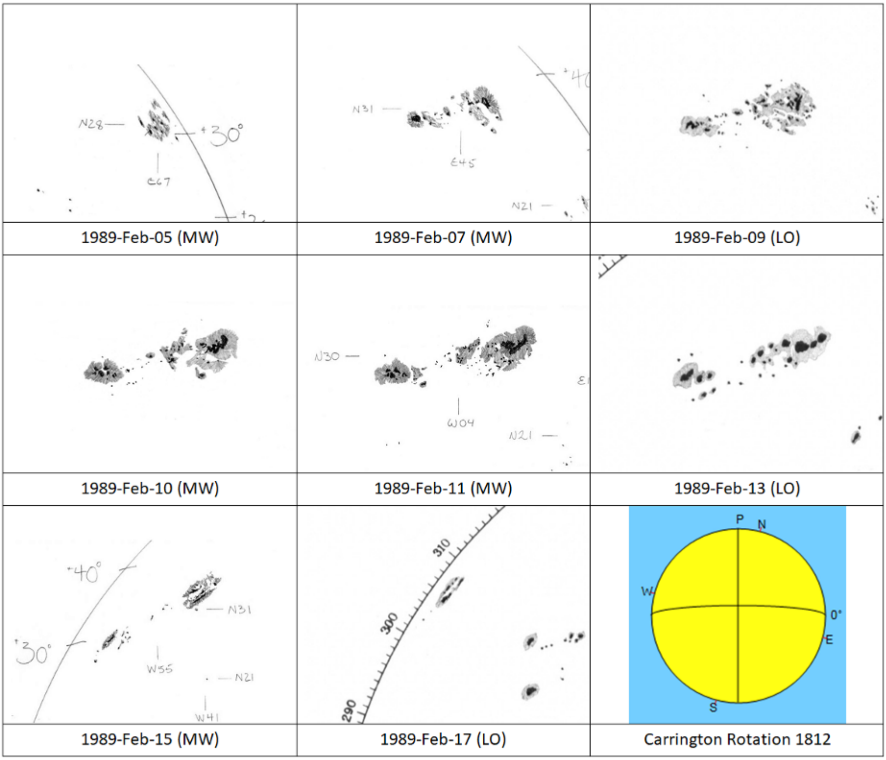


Figure 33. Passage of NOAA Active Region 5354 based on Mt Wilson (MW) and Locarno (LO) Drawings

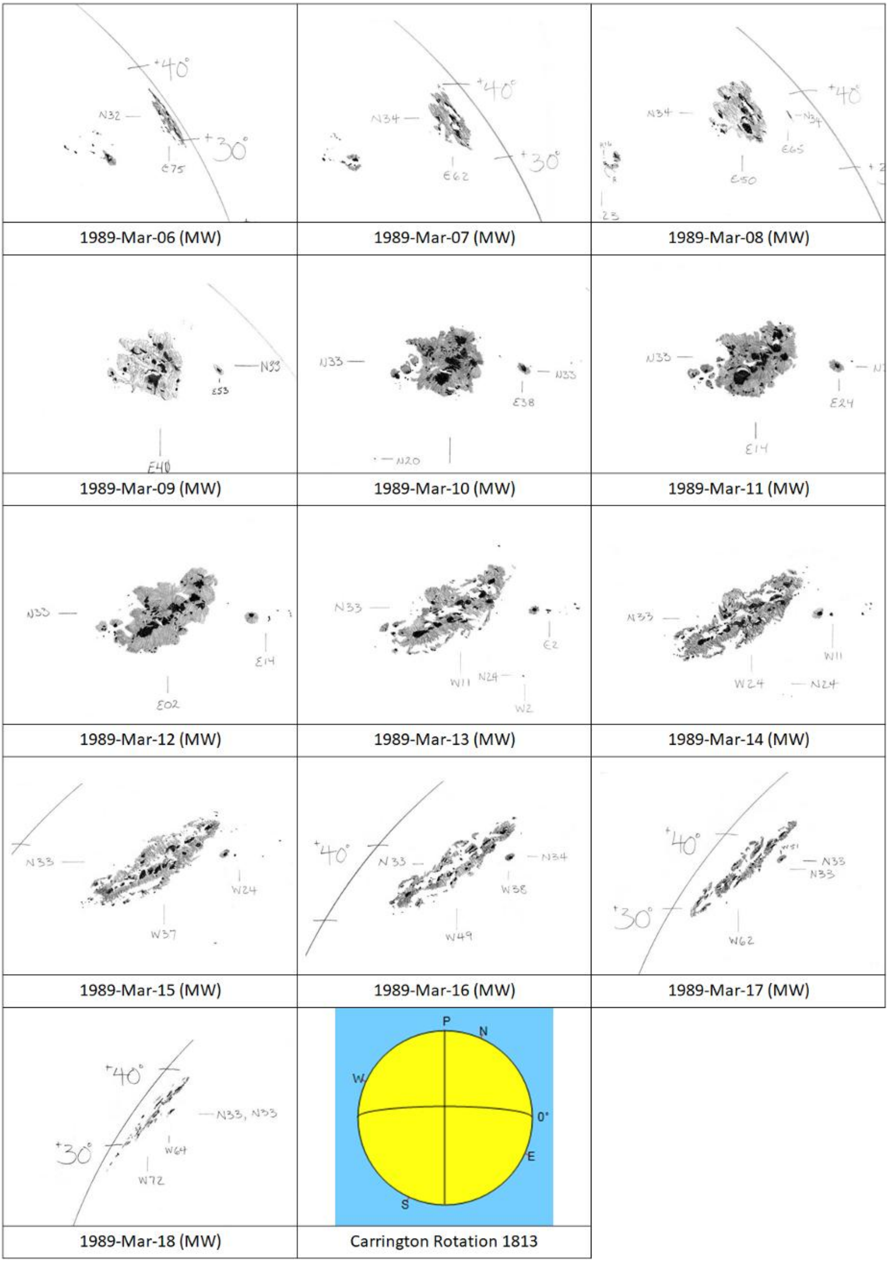


Figure 34. Passage of NOAA Active Region 5395 based on Mt Wilson (MW) Drawings

NOAA	MW	HK	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
5354	25026	7024	1989 Feb 05	1989 Feb 17	31.5°	282.0°	2402	1989 Feb 07
5395	**25081**	**7042**	**1989 Mar 06**	**1989 Mar 18**	**33.3°**	**255.3°**	**4201**	**1989 Mar 14**
5441	25154	7064	1989 Apr 05	1989 Apr 16	34.8°	234.3°	423	1989 Apr 10

Table 7. Information on Group 25081, previous and subsequent rotations

The group returned on the next rotation as an irregular penumbral sunspot on March 6. As the group progressed towards the central meridian, it could be seen that the sunspot had a similar extent in both latitude and longitude. However, from March 11, the group began to elongate in longitude while keeping the same latitude extent. On March 13 the longitude extent was 18°. Many areas of photosphere could be seen within this complex sunspot as shown in Figure 34 and Figure 30. It obtained its maximum area of 4200 MSH when mid-way between the central meridian and the western limb. As it progressed towards the west, the sunspot appeared to breakup into many parts. It was very close to the limb on March 18.

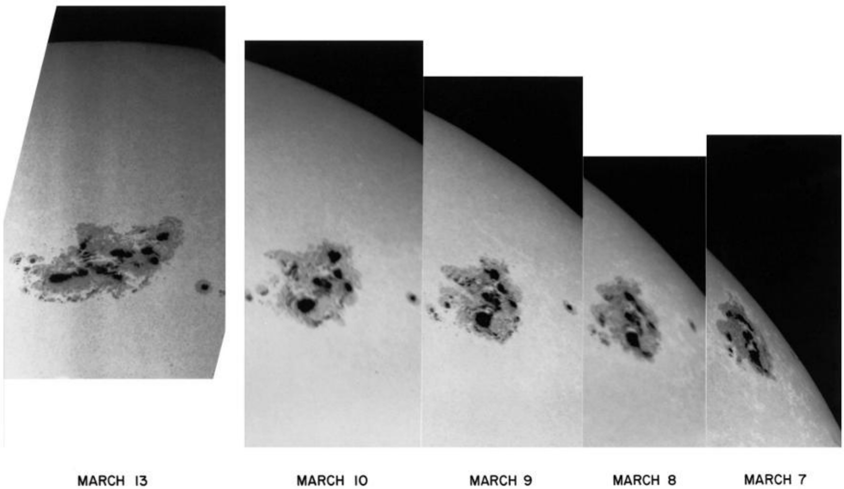


Figure 35a. Passage of NOAA Active Region 5395 1989 March 7 to 13 (National Solar Observatory [25])

On the third and final rotation, the group was much diminished consisting of a penumbral sunspot and a few leading pores. The penumbral sunspot decayed as the group progressed across the disk to leave a single sunspot close to the western limb on April 16 (Figure 36). The area evolution of this great group is shown in Figure 37.

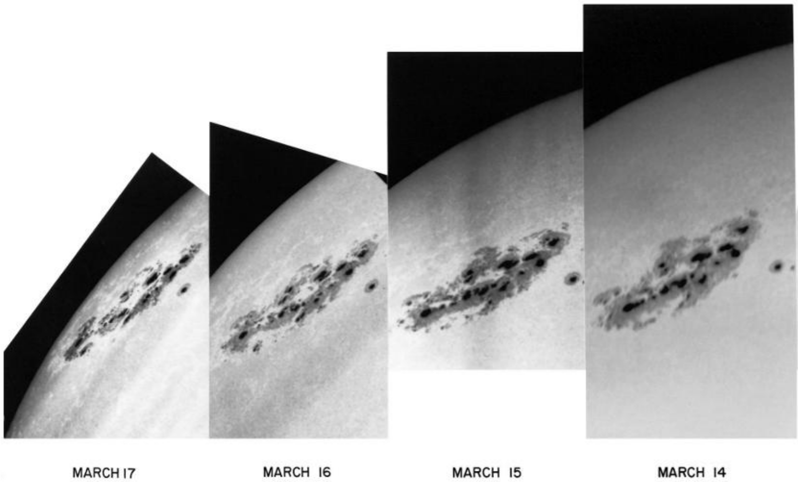


Figure 35b. Passage of NOAA Active Region 5395 1989 March 14 to 17 (National Solar Observatory [25])

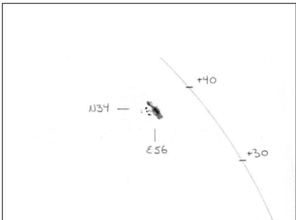
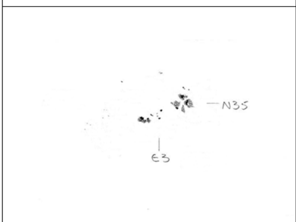
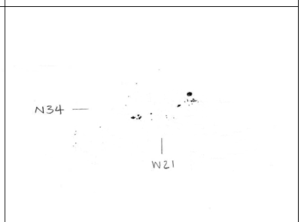
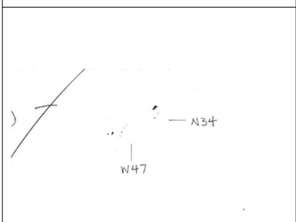
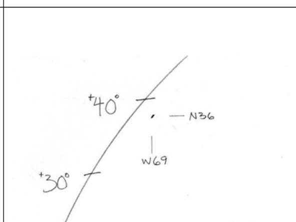
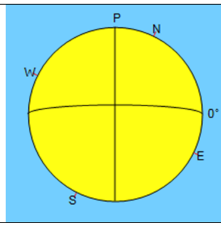
		
1989-Apr-06 (MW)	1989-Apr-08 (MW)	1989-Apr-09 (HK)
		
1989-Apr-10 (MW)	1989-Apr-11 (MW)	1989-Apr-12 (MW)
		
1989-Apr-14 (MW)	1989-Apr-16 (MW)	Carrington Rotation 1814

Figure 36. Passage of NOAA Active Region 5441 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

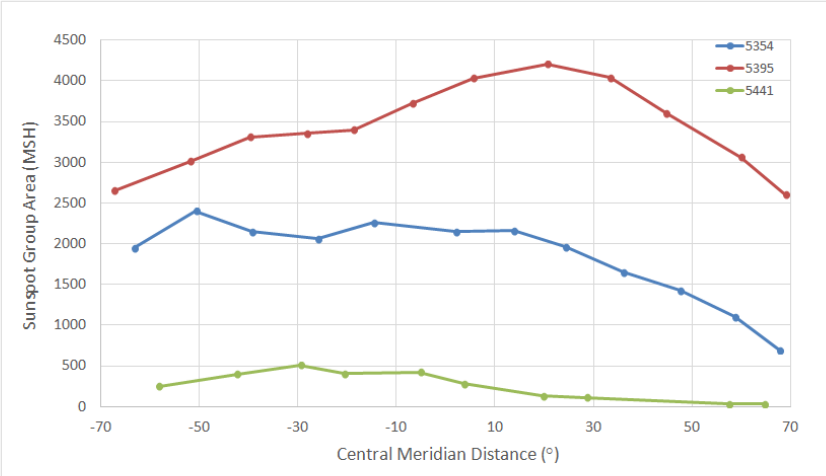


Figure 37. Debrecen Sunspot Area for NOAA Active Regions 5354, 5395 and 5441

As expected for a high latitude group, the differential rotation longitude evolution from rotation to rotation is quite large as shown in Figure 38 based on the mid-longitude of the group. The linear fit to the longitude drift, the black line in Figure 38 gives a mean drift of 0.9° per day or 23.6° per rotation. Figure 79 shows that the measured differential rate is greater than all the predicted rotation rates and indicates a proper motion of 9° relative to the Maunder curve.

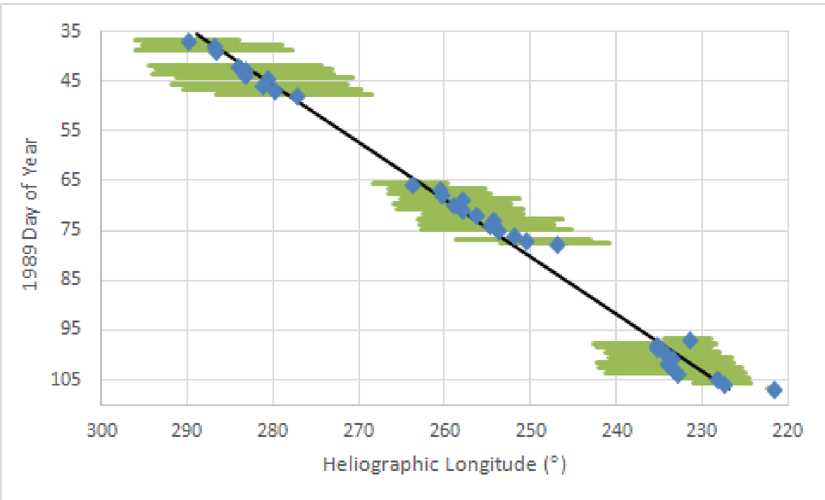


Figure 38. Longitude evolution of NOAA Active Regions 5354, 5395 and 5441

October 2014 (NOAA Active Region 12192)

On 2014 October 17, the group that was to become the largest group of Cycle 24 [26], AR 12192, rotated onto the disk at a latitude of 12°S as a complex group where the follower was the largest penumbral sunspot. Over the next two days more of the large irregular follower could be seen which included a main penumbral sunspot and several smaller sunspots. Its total area was estimated at 2806 MSH on the October 19. By October 21 AR 12192 had became much more complex with many umbrae and several regions of photosphere within the main penumbral sunspot and its area grew to 3253 MSH – see Figure 39. On the following few days the group continued to increase in size and more photosphere could be seen in the middle portion of the group. The maximum area was obtained on October 24 at 4419 MSH (Figure 41) and there was a split of the main penumbral sunspots with the new follower being the largest penumbral sunspot. AR 12192 reduced in size as it progressed towards the western limb and it was last seen on October 28. Throughout its passage across the solar disk, AR 12192 remained a complex bipolar group.

The author saw AR 12192 with the protected naked eye on the October 19 to 23, 25, 27 and 28 (from October 21 to 23 it was seen as an elongated sunspot while on October 25 two distinct naked eye sunspots were seen but on October 27 and 28 it was once again seen as one sunspot). Further images of AR 12192 are shown in Figure 40.

As indicated in Table 8, this great sunspot group was also seen on the previous rotation as NOAA active region AR 12172. As shown in Figure 42, the group rotated onto the disk on September 20. When further on the disk, it was seen as a bipolar group having an area of 1056 MSH on the September 22. As it progressed towards the central meridian, a large number of pores developed around and within the group (the southern collection of these pores were assigned as a different group). As the group progressed towards the western limb, the number of sunspots reduced as did the area of the group but only slightly (Figure 41).

NOAA Active Region	Locarno Group Number	Appearance & Disappearance Dates		Mean Lat.	Mean Long.	Max. Area (MSH)	Max. Area Date
12172	319/325	2014 Sep 20	2014 Oct 03	-11.0°	241.0°	1056	2014 Sep 22
12192	**346**	**2014 Oct 17**	**2014 Oct 30**	**-13.7°**	**244.9°**	**4419**	**2014 Oct 24**
12209	371	2014 Nov 12	2014 Nov 26	-15.1°	244.2°	1688	2014 Nov 15

Table 8. Information on Group 12192, previous and subsequent rotations

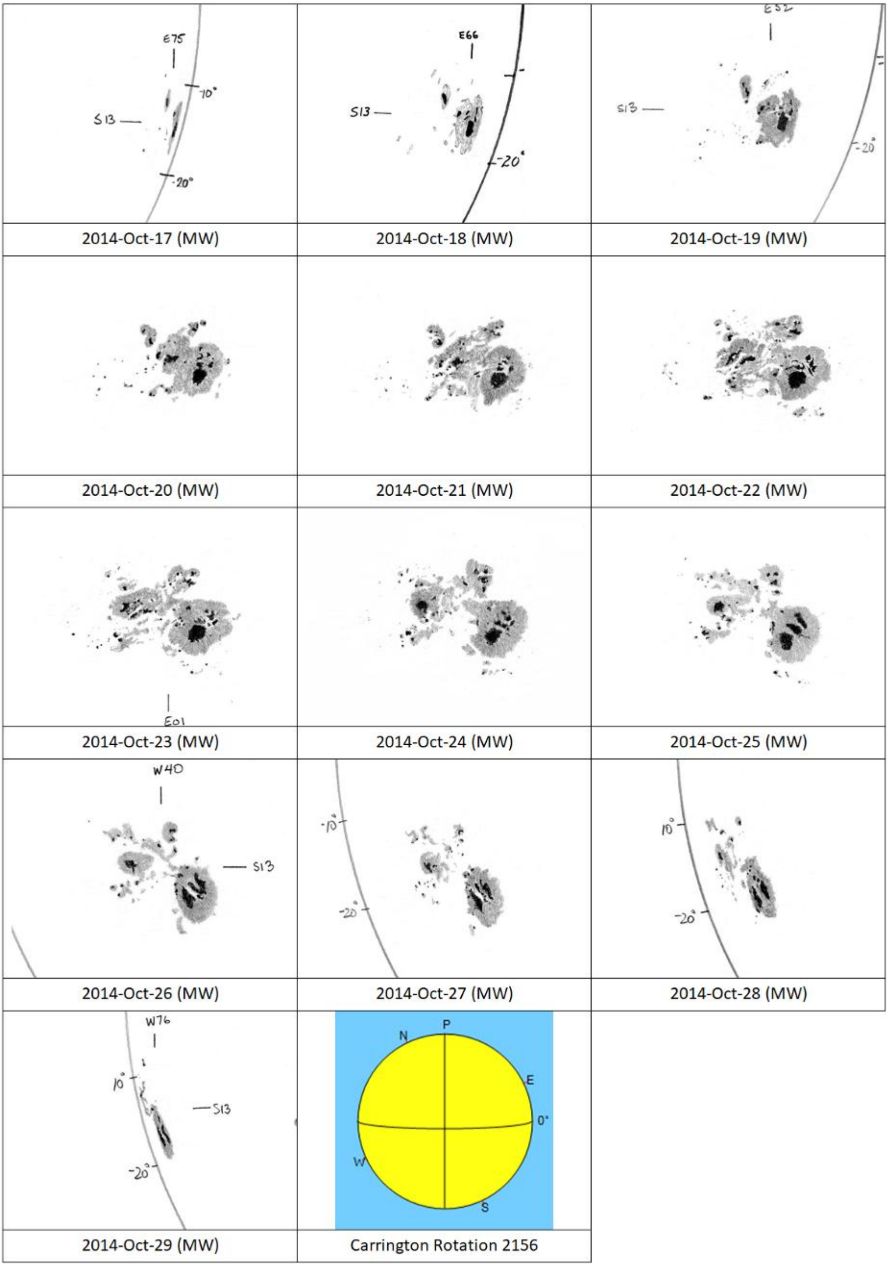


Figure 39. Passage of NOAA Active Region 12192 based on Mt Wilson (MW) Drawings

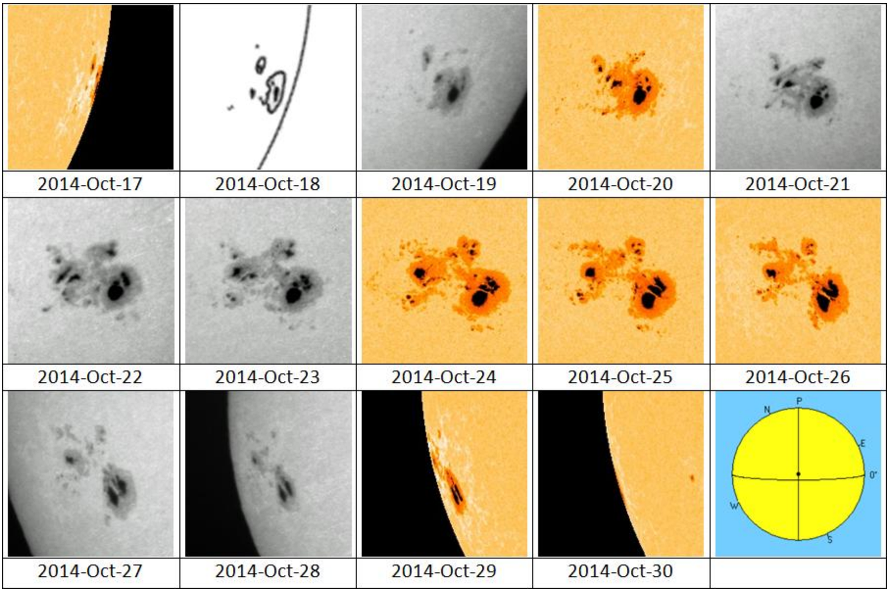


Figure 40. Passage of NOAA Active Region 12192 based on SDO/HMI Images and the author's drawing and photographs

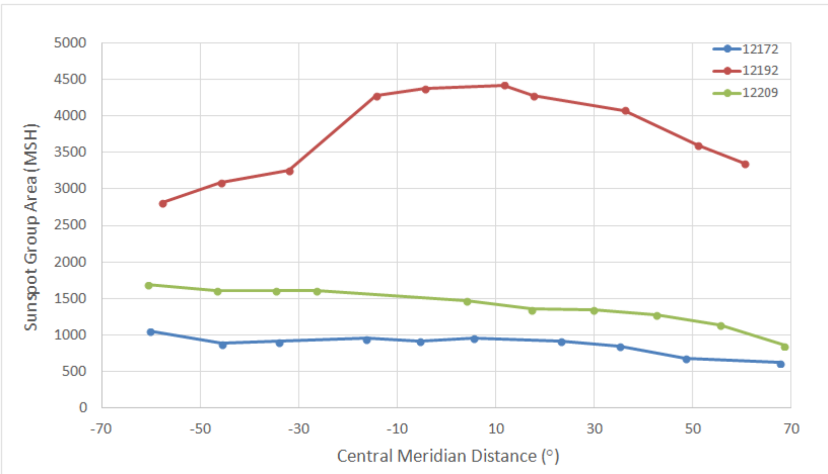


Figure 41. Debrecen Sunspot Area for NOAA Active Regions 12172, 12192 and 12209

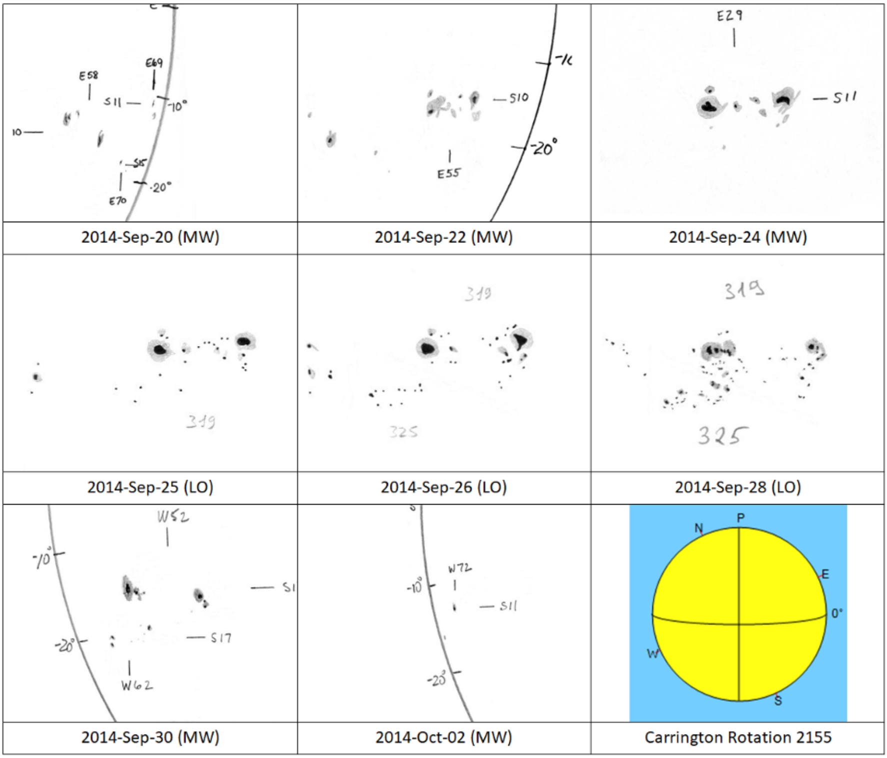


Figure 42. Passage of NOAA Active Region 12172 based on Mt Wilson (MW) and Locarno (LO) Drawings

AR 12172 was also seen on the next rotation as AR 12209 appearing on November 12. As shown in Figure 43, the follower was still the dominate sunspot. As the group progressed across the disk, the main sunspot formed into a circular region of penumbra with photosphere in the middle. It maximum area of 1688 MSH when still near the eastern limb on November 15. There were very few other sunspots and pores within the group. It reduced in size as it progressed across the disk, having rotated off the disk on November 26.

Over the three rotations, the mean latitude of this great sunspot group reduced slightly from 11°S to 15°S. Figure 44 shows the longitude evolution – given the latitude of this group there is very little drift in longitude (the black line is based on the mean longitude of the main following sunspot for the second and third rotations). As shown in Figure 79, the longitude drift was very similar to that of the 1951 great sunspot group (at a very similar latitude).

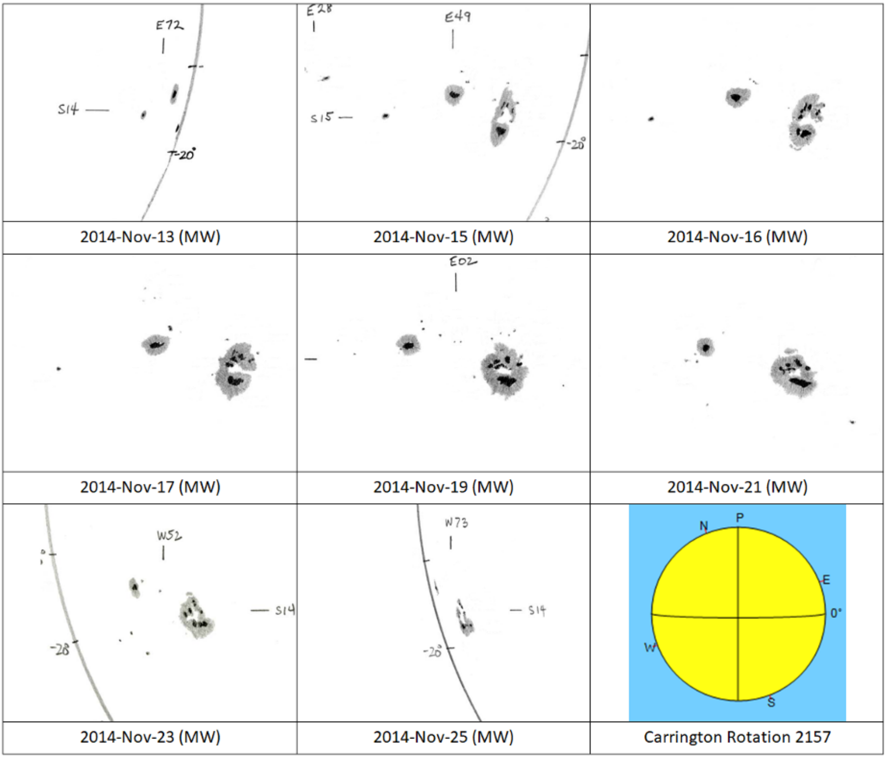


Figure 43. Passage of NOAA Active Region 12209 based on Mt Wilson (MW) Drawings

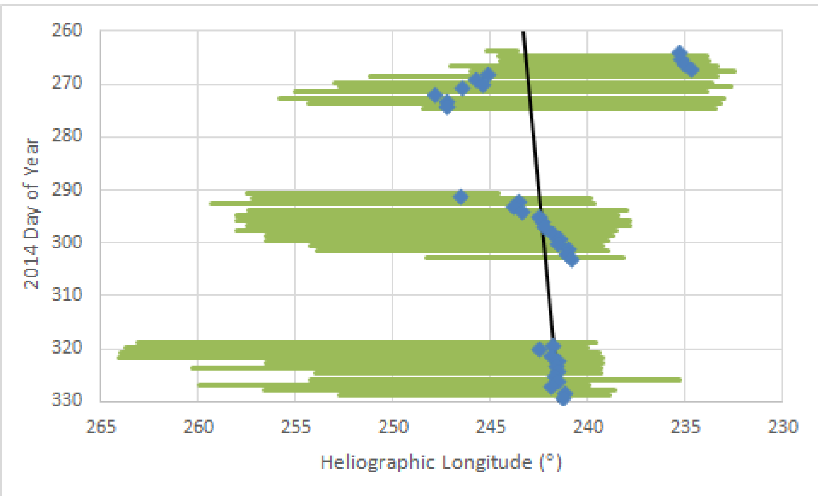


Figure 44. Longitude evolution of NOAA Active Regions 12172, 12192 and 12209

Great Groups with areas between 3000 and 4000 MSH

As an extension to the above seven great sunspot groups, Table 9 gives details of groups with maximum areas between 3000 and 4000 MSH. The group number in the table is either the Greenwich Group or NOAA Active Region number (before or after 1977). Figure 45 to Figure 68 show the passage of these groups in reducing size order. Note that as the Mt Wilson drawings began in 1917, photographs are shown instead for the groups from 1892 and 1905.

Group	Date	Area (MSH)	Mean Lat.	Mean Long.
6368	1990 Nov 16	3872	18.4°	25.1°
9861	1926 Jan 19	3716	20.9°	35.0°
12673	1938 Jan 21	3627	17.1°	225.0°
7977	1917 Feb 14	3590	-15.8°	9.3°
10486	2003 Nov 01	3388	-18.0°	285.9°
9393	2001 Mar 29	3387	18.0°	154.6°
12902	1938 Jul 20	3379	-12.3°	39.6°
12553	1937 Oct 05	3340	9.4°	182.1°
5441	1905 Feb 02	3339	-15.3°	329.3°
12455	1937 Jul 28	3303	31.5°	356.1°
4474	1984 Apr 26	3274	-12.3°	340.3°
6555	1991 Mar 23	3257	-23.9°	184.3°
5528	1989 Jun 16	3249	20.4°	95.5°
6850	1991 Oct 27	3234	-12.0°	183.6°
21482	1968 Feb 01	3202	12.7°	165.6°
8181	1917 Aug 09	3178	16.2°	129.2°
3804	1982 Jul 11	3092	13.3°	321.4°
13937	1941 Sep 21	3088	11.6°	210.3°
13394	1939 Sep 06	3054	-13.8°	348.3°
5060	1988 Jul 02	3047	-19.8°	4.5°
3776	1982 Jun 13	3040	12.1°	315.2°
2421	1892 Feb 10	3038	-28.4°	255.7°
2779	1980 Nov 13	3030	-11.2°	99.2°
13024	1938 Oct 12	3003	16.9°	305.9°

Table 9. Sunspot groups with maximum area between 3000 and 4000 MSH [2]

On 1859 September 1, Richard Carrington [29], [30], [31] and Richard Hodgson [32] independently observed one of the first white light solar flares. Figure 69 shows Carrington's drawing for this date and the area measurement of the group responsible for the flare using Helio Viewer: 3100 MSH to make this group the 24th largest recorded sunspot group.

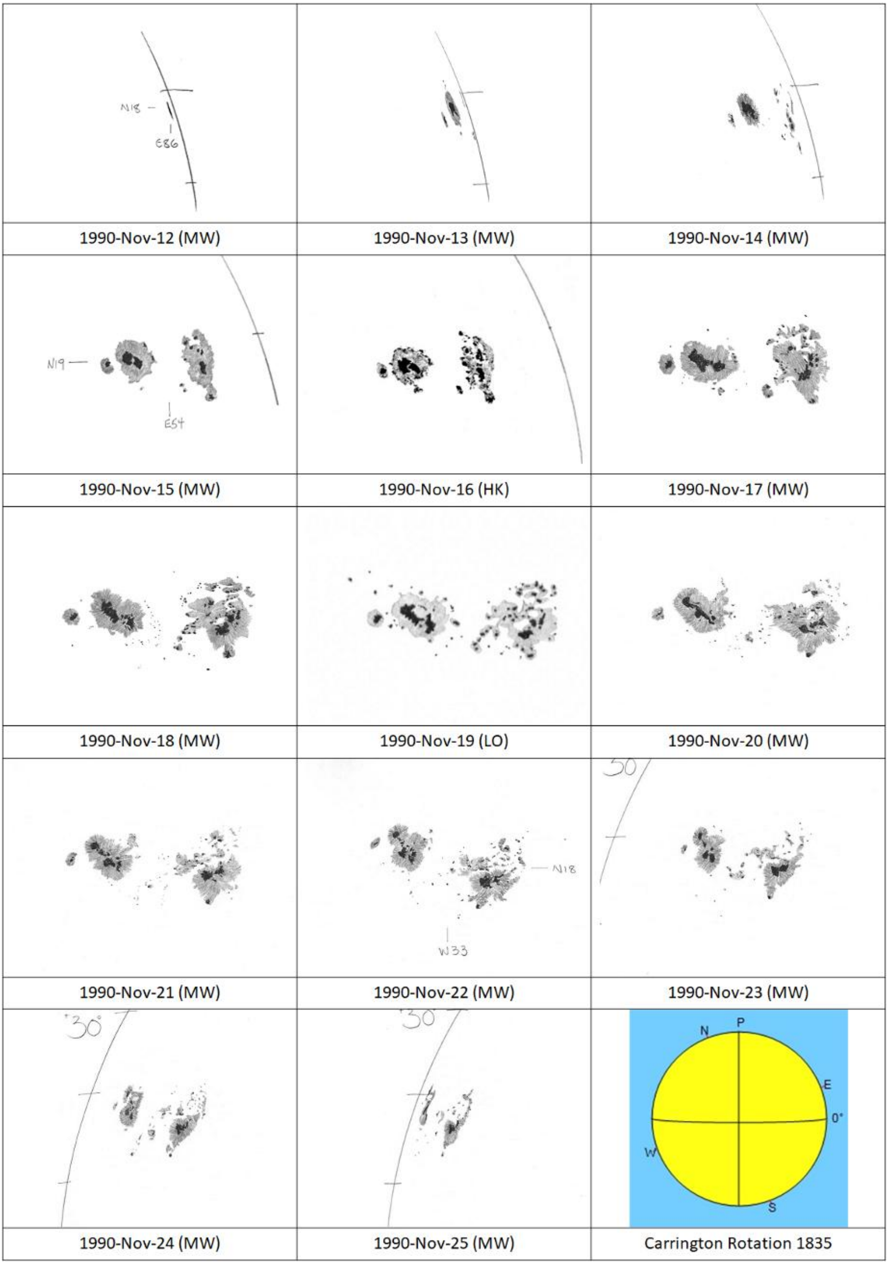


Figure 45. Passage of NOAA Active Region 6368 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

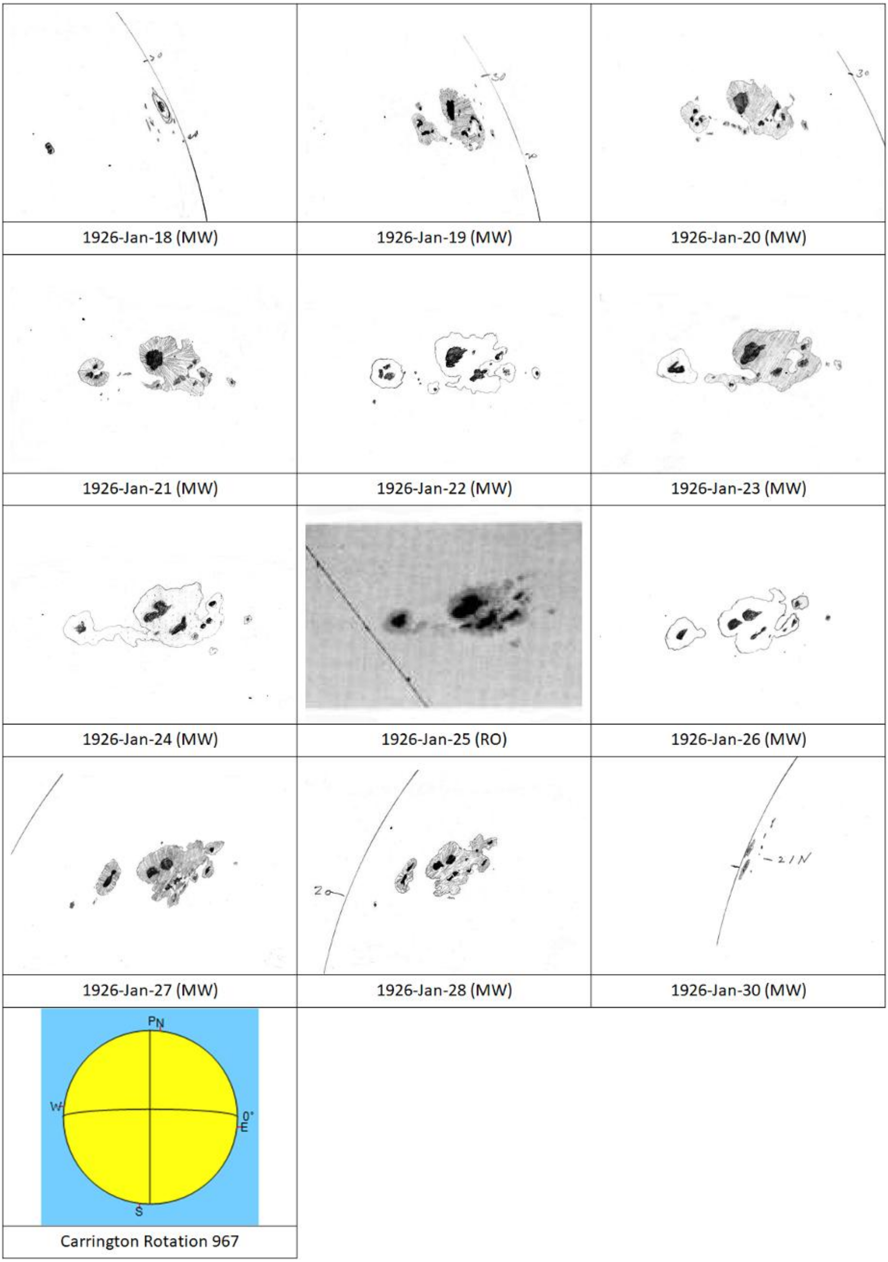


Figure 46. Passage of Greenwich Group 9861 based on Mt Wilson (MW) Drawings and a Royal Observatory, Greenwich (RO) Photograph [27]

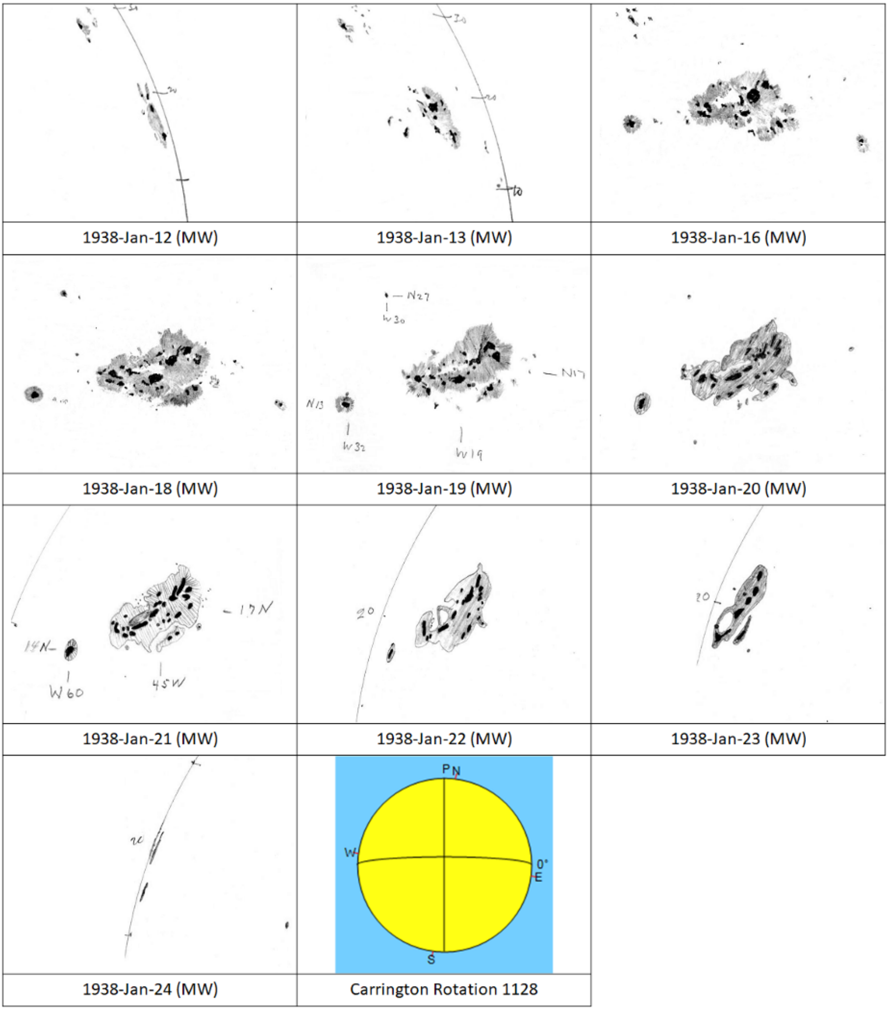


Figure 47. Passage of Greenwich Group 12673 based on Mt Wilson (MW) Drawings

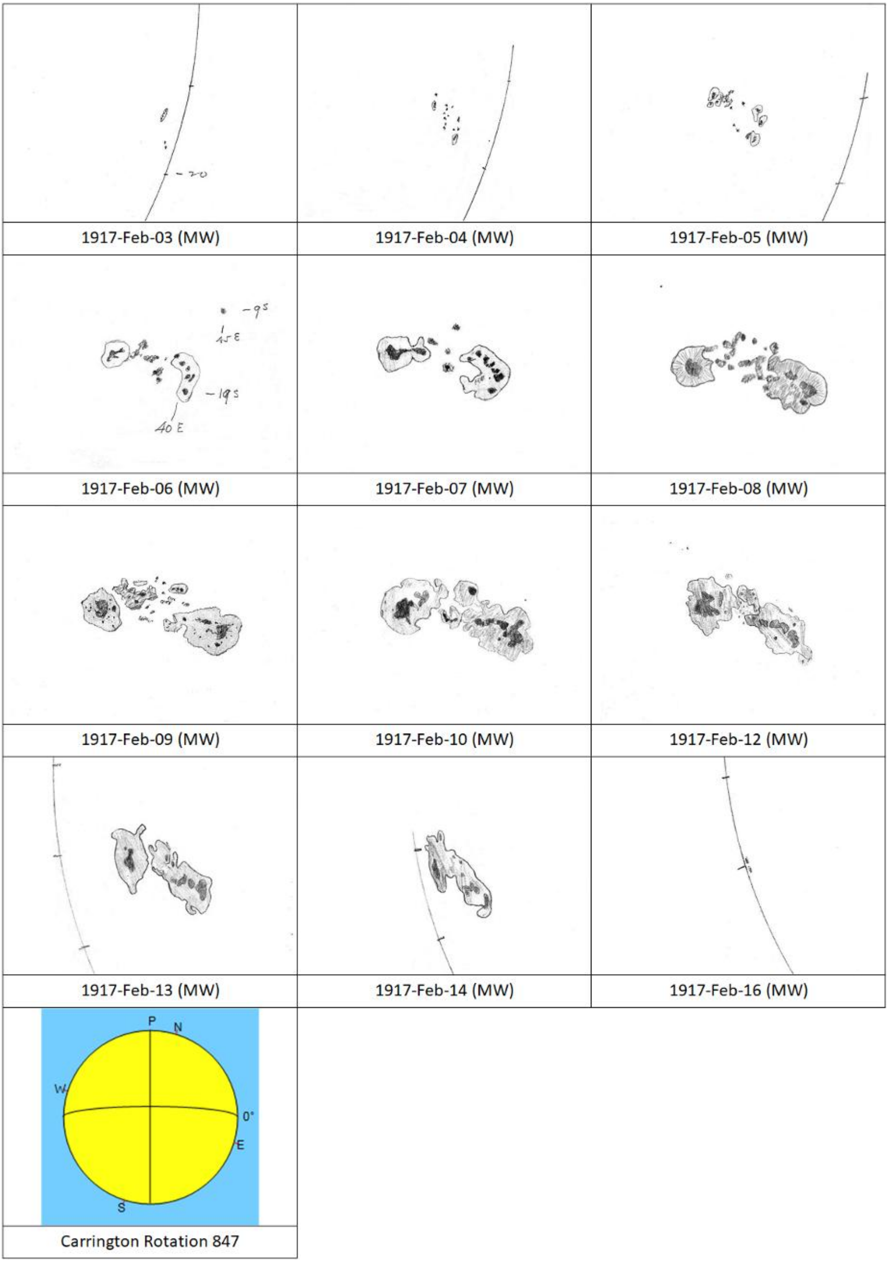


Figure 48. Passage of Greenwich Group 7977 based on Mt Wilson (MW) Drawings

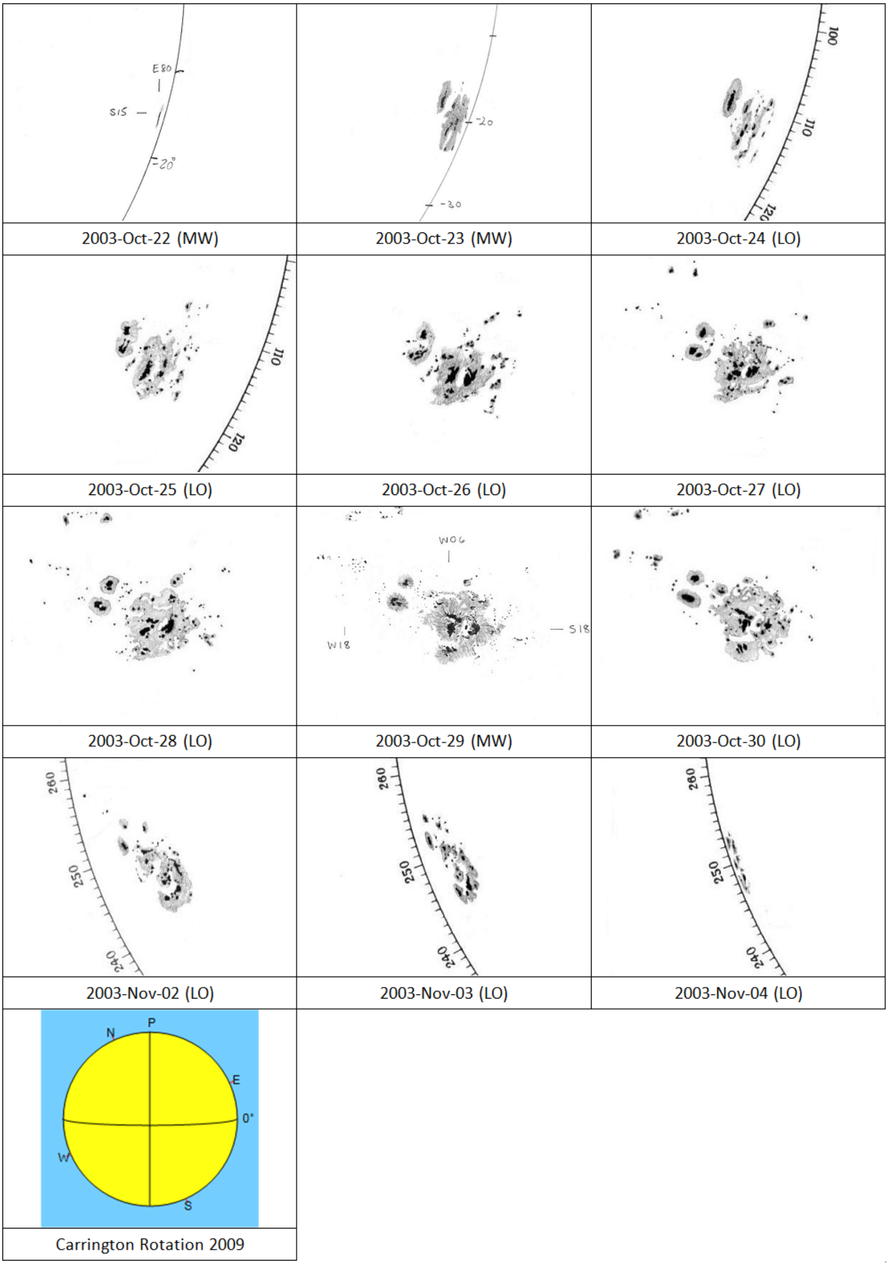


Figure 49. Passage of NOAA Active Region 10486 based on Locarno (LO) and Mt Wilson (MW) Drawings

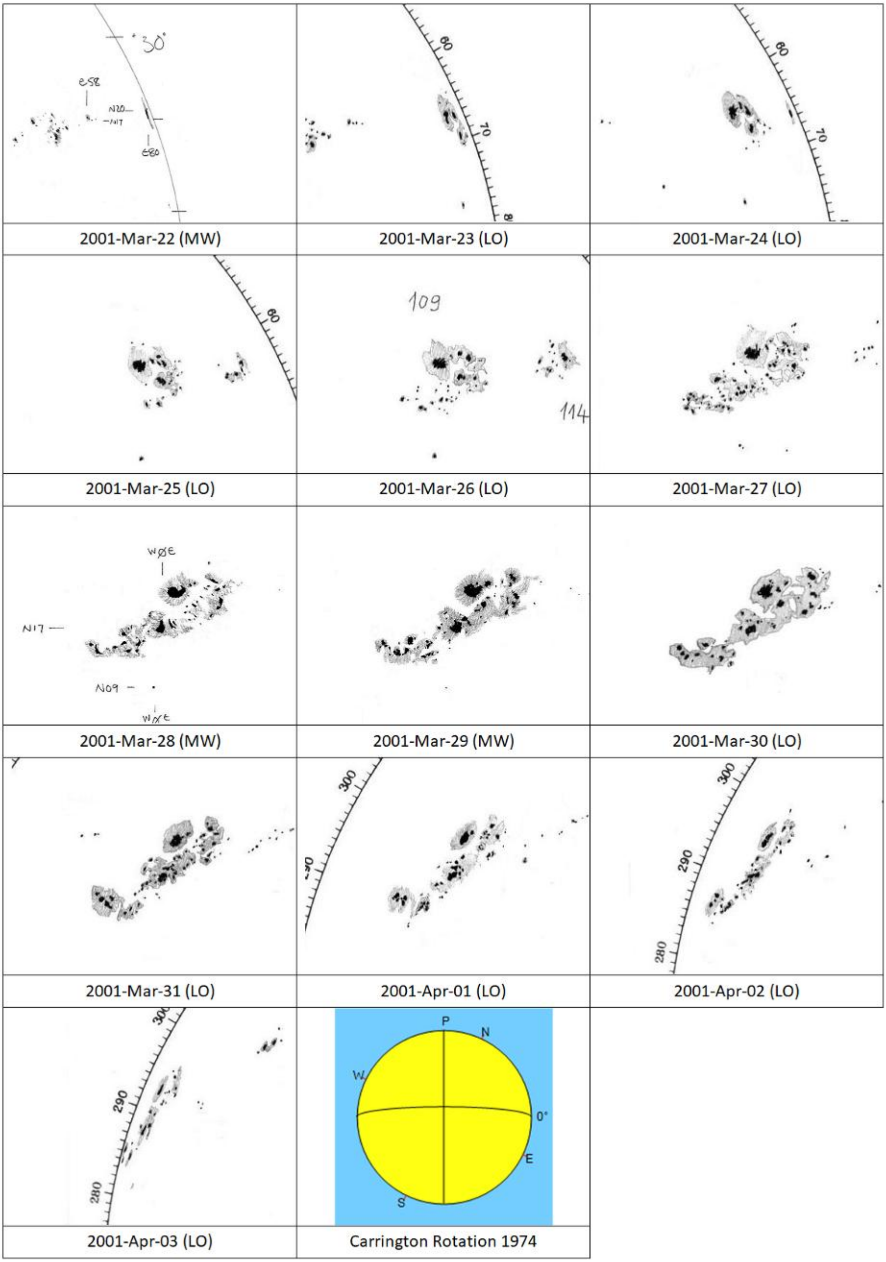


Figure 50. Passage of NOAA Active Region 9393 based on Locarno (LO) and Mt Wilson (MW) Drawings

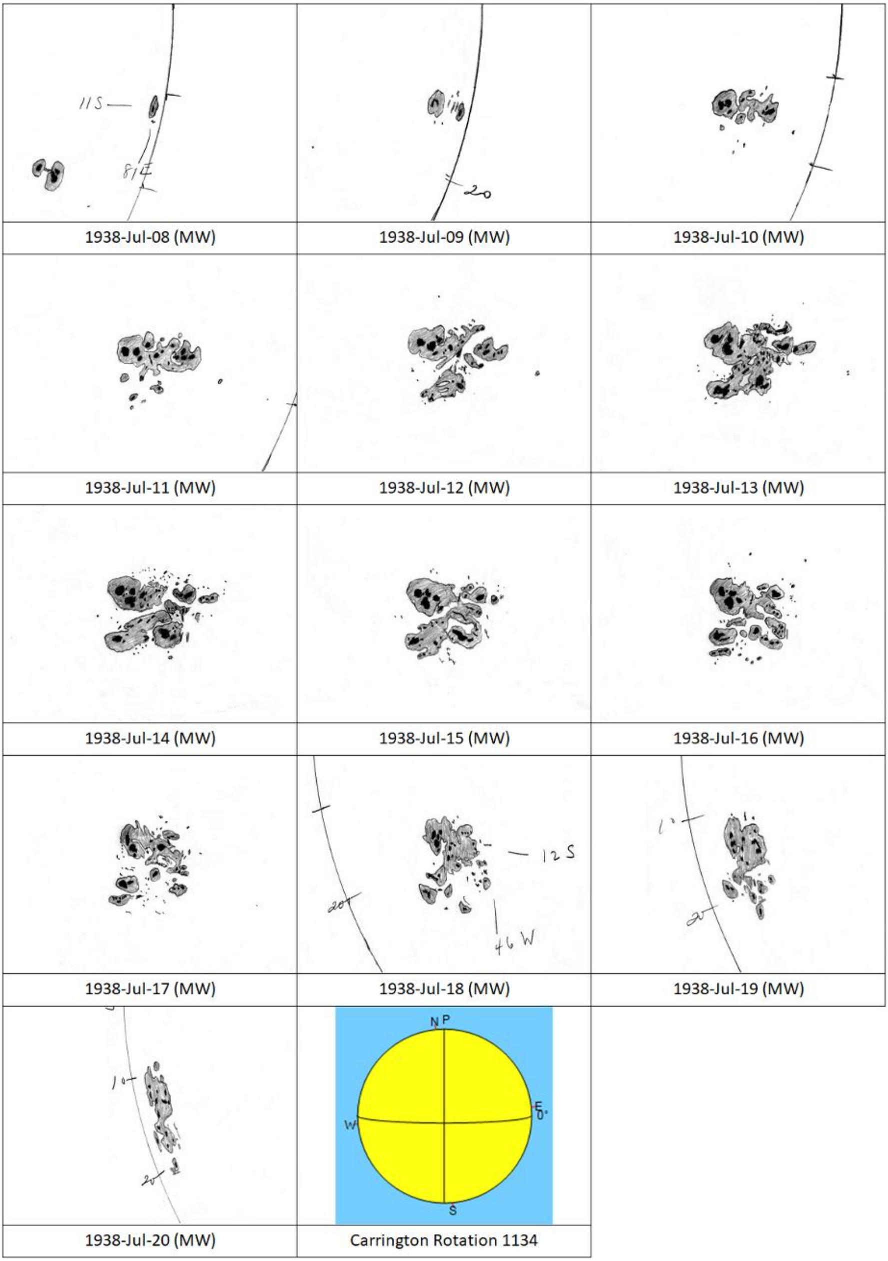
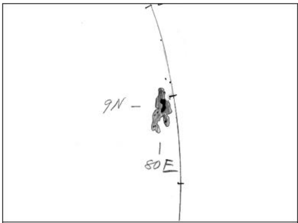
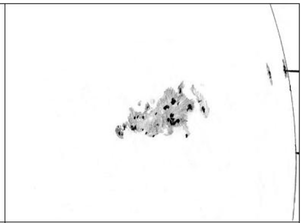


Figure 51. Passage of Greenwich Group 12902 based on Mt Wilson (MW) Drawings

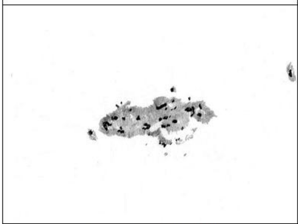


1937-Sep-28 (MW)

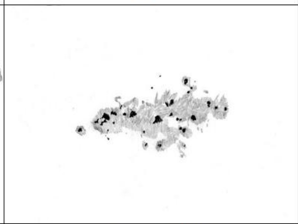
1937-Sep-29 (MW)



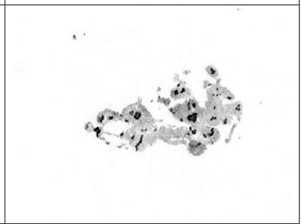
1937-Sep-30 (MW)



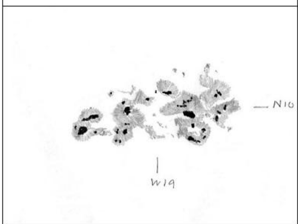
1937-Oct-01 (MW)



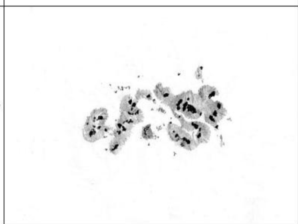
1937-Oct-02 (MW)



1937-Oct-04 (MW)

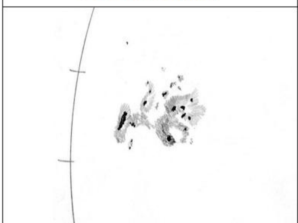


1937-Oct-05 (MW)

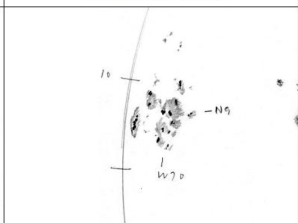


1937-Oct-06 (MW)

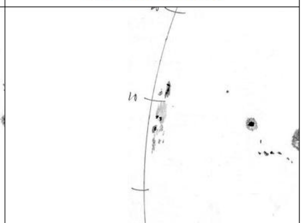
1937-Oct-07 (MW)



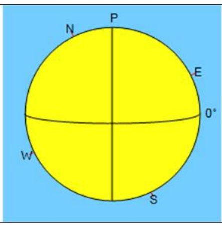
1937-Oct-08 (MW)



1937-Oct-09 (MW)



1937-Oct-10 (MW)



Carrington Rotation 1124

Figure 52. Passage of Greenwich Group 12553 based on Mt Wilson (MW) Drawings

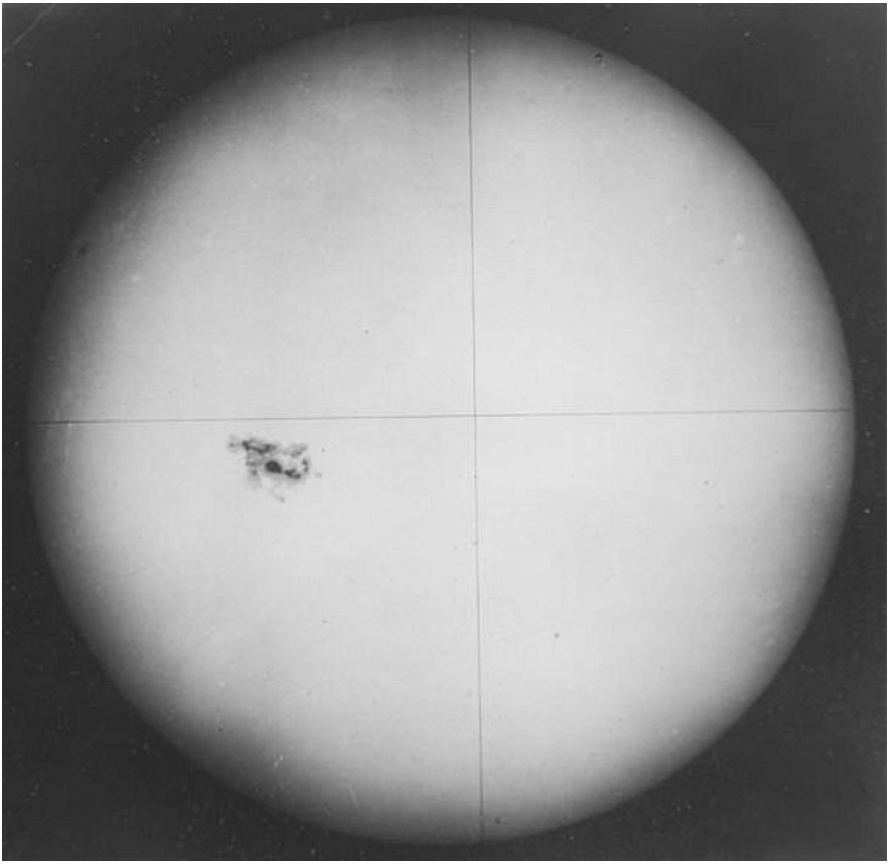


Figure 53a. Greenwich Group 5441. Royal Observatory, Greenwich Photograph 1905 February 2 [24]

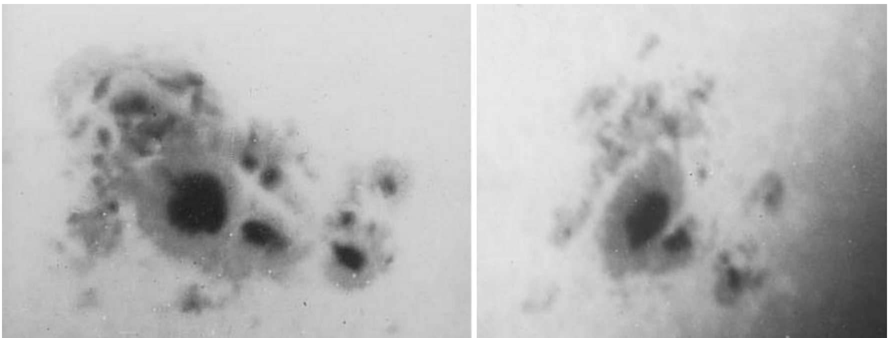


Figure 53b. Greenwich Group 5441. Royal Observatory, Greenwich Photograph 1905 February 5 (left) and February 8 [24]

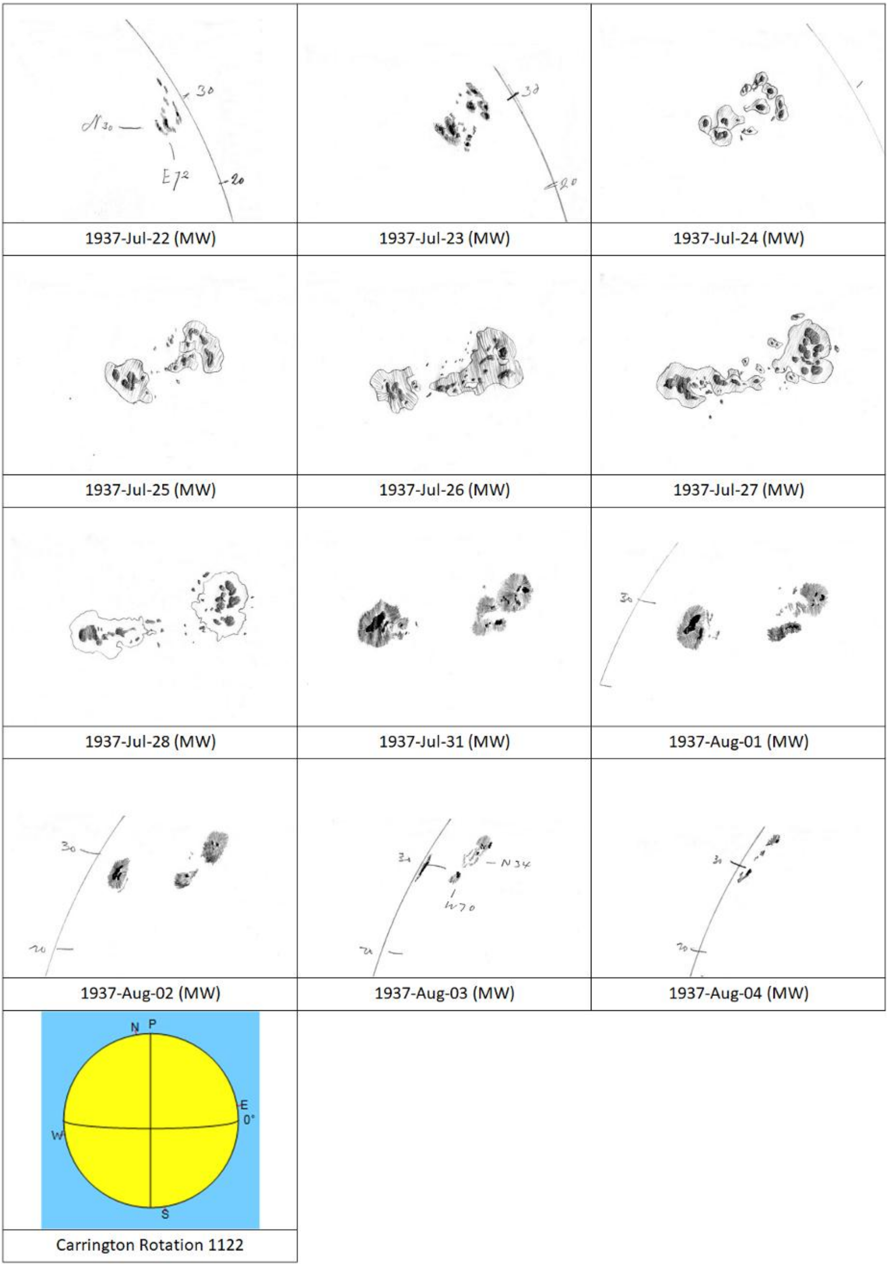


Figure 54. Passage of Greenwich Group 12455 based on Mt Wilson (MW) Drawings

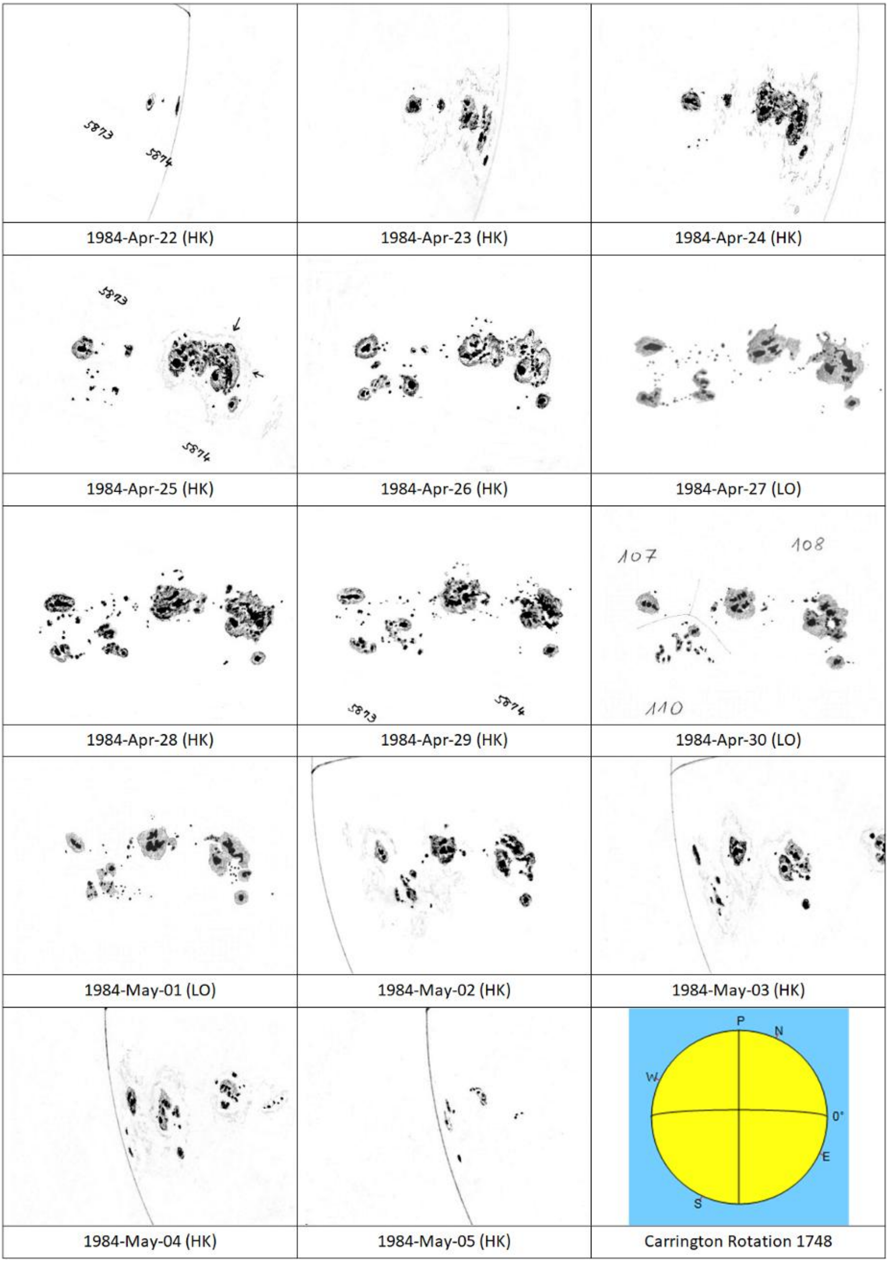


Figure 55. Passage of NOAA Active Region 4474 based on Hisako Koyama (HK) and Locarno (LO) Drawings

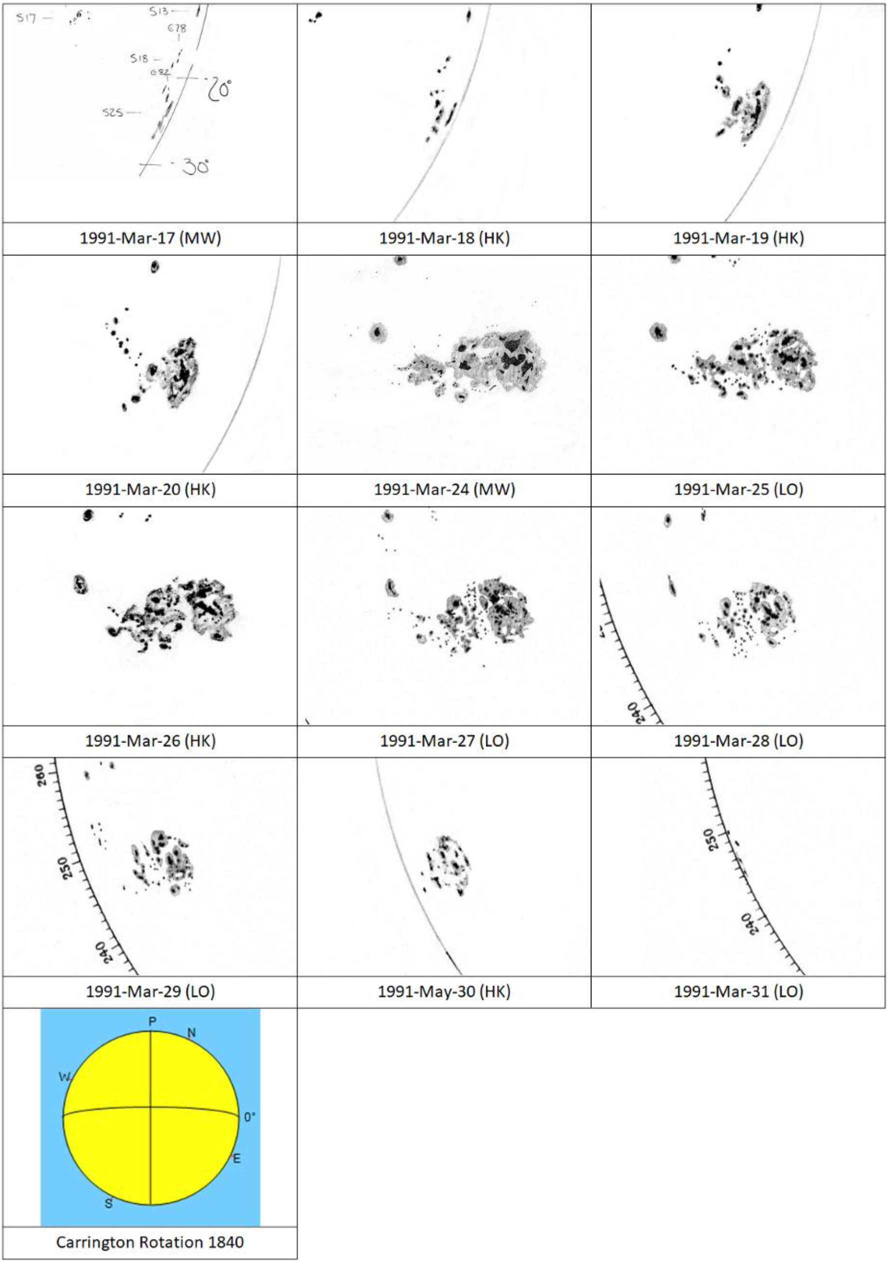


Figure 56. Passage of NOAA Active Region 6555 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

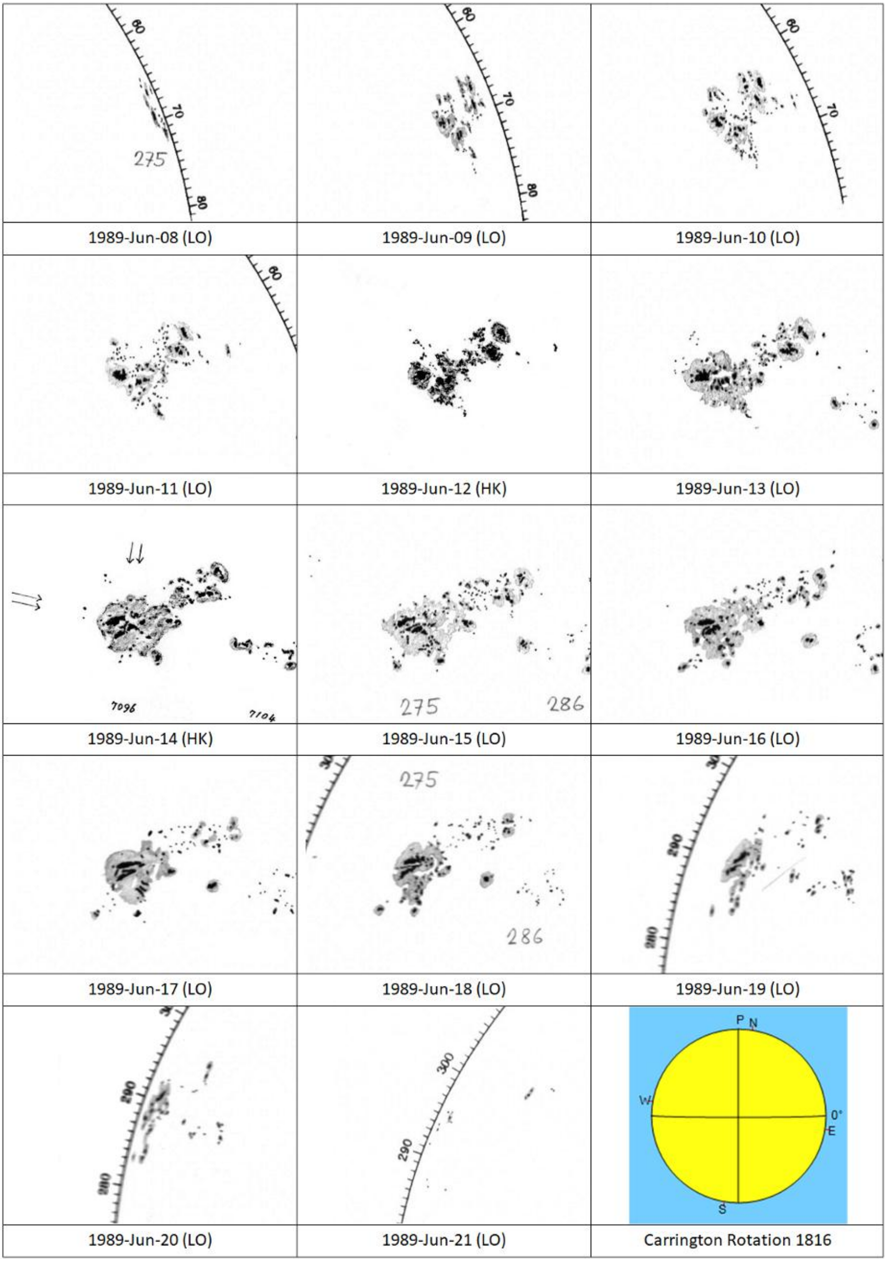


Figure 57. Passage of NOAA Active Region 5528 based on Hisako Koyama (HK) and Locarno (LO) Drawings

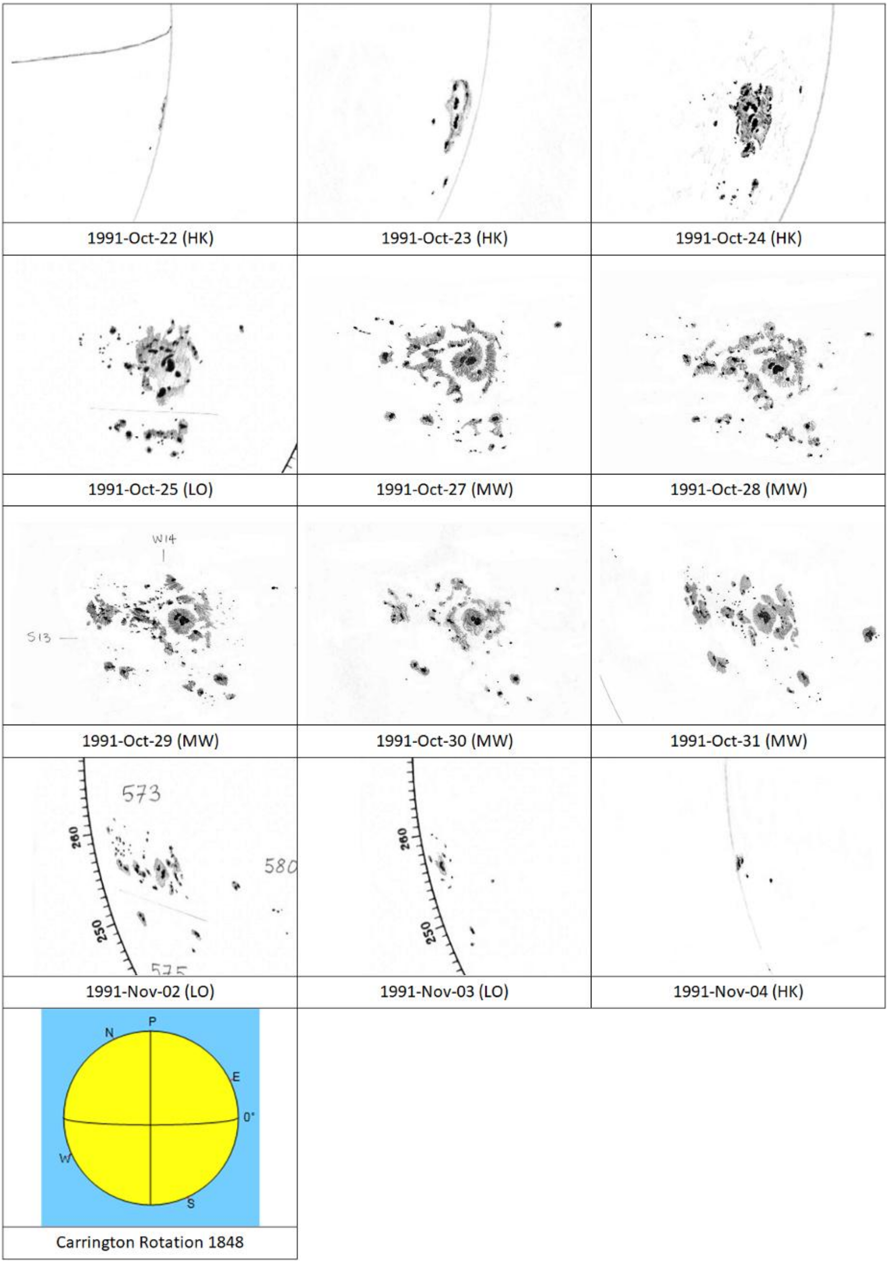


Figure 58. Passage of NOAA Active Region 6850 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

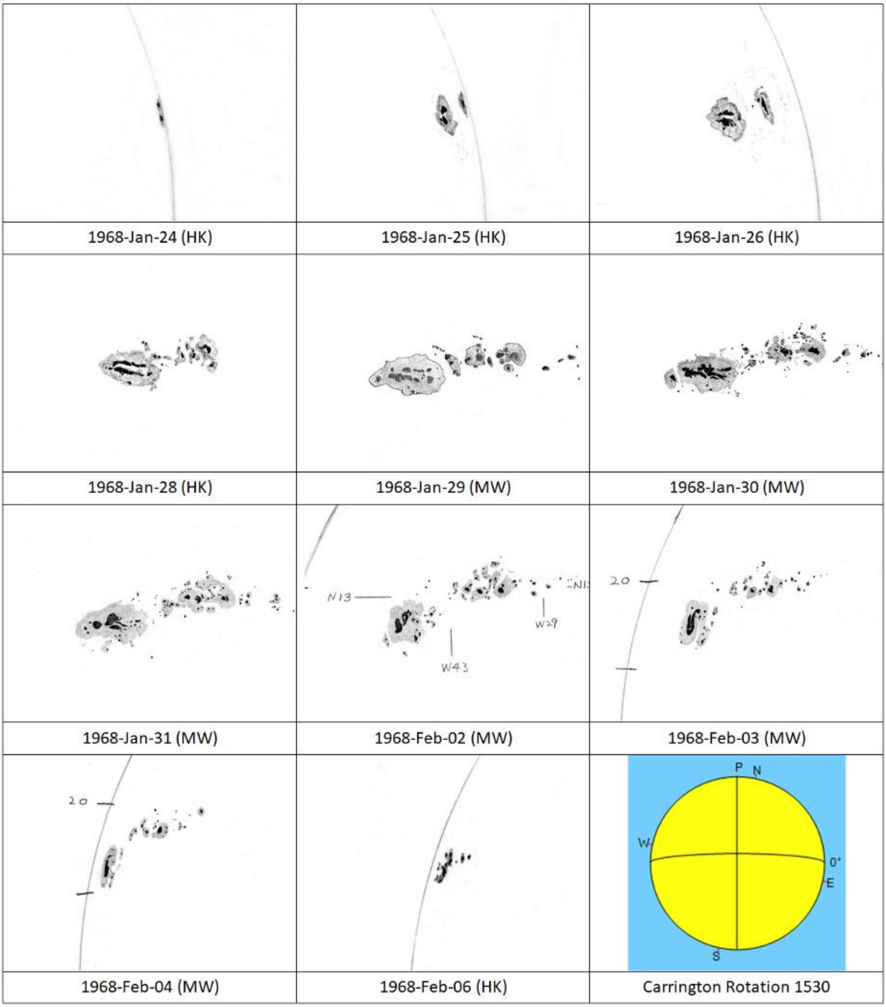


Figure 59. Passage of Greenwich Group 21482 based on Mt Wilson (MW) and Hisako Koyama (HK) Drawings

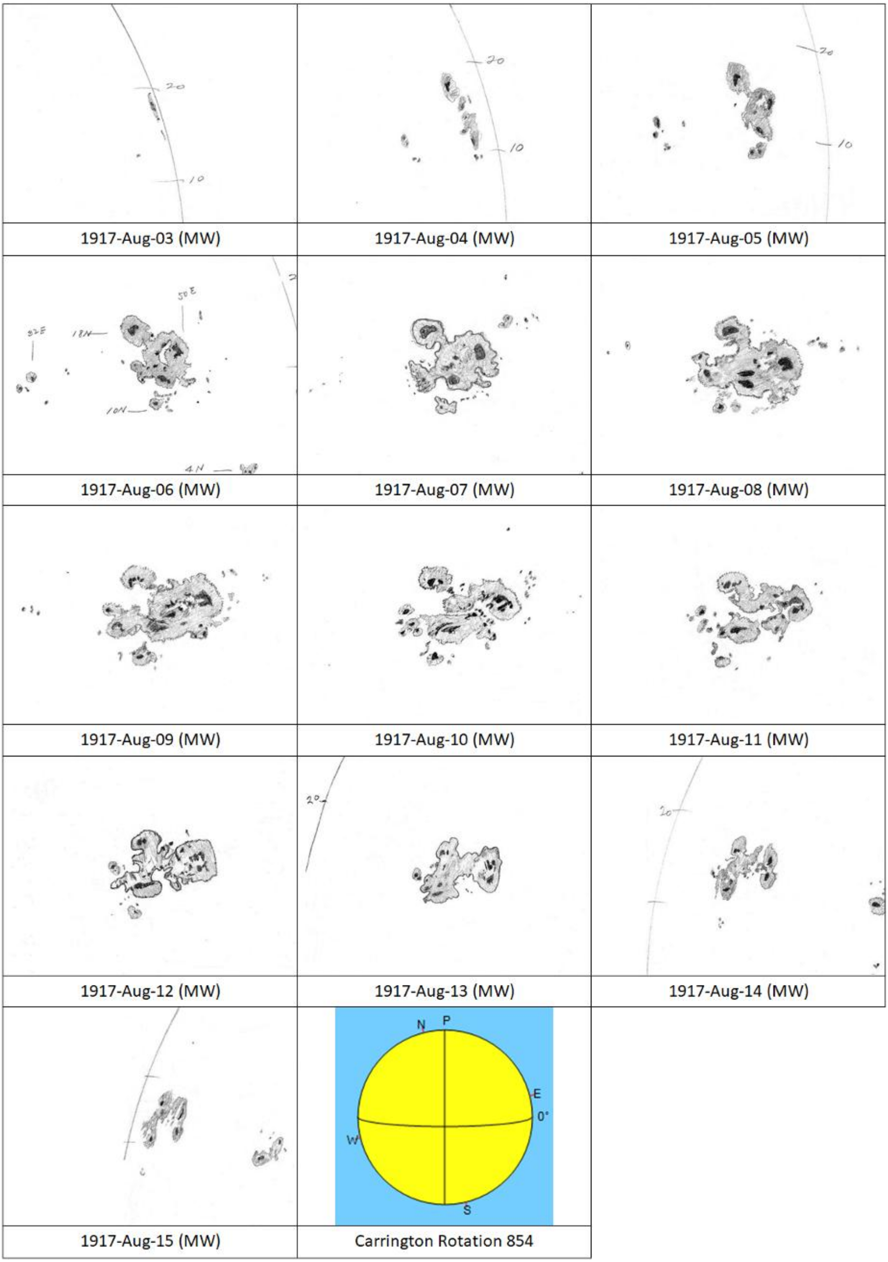


Figure 60. Passage of Greenwich Group 8181 based on Mt Wilson (MW) Drawings - see also Figure 89

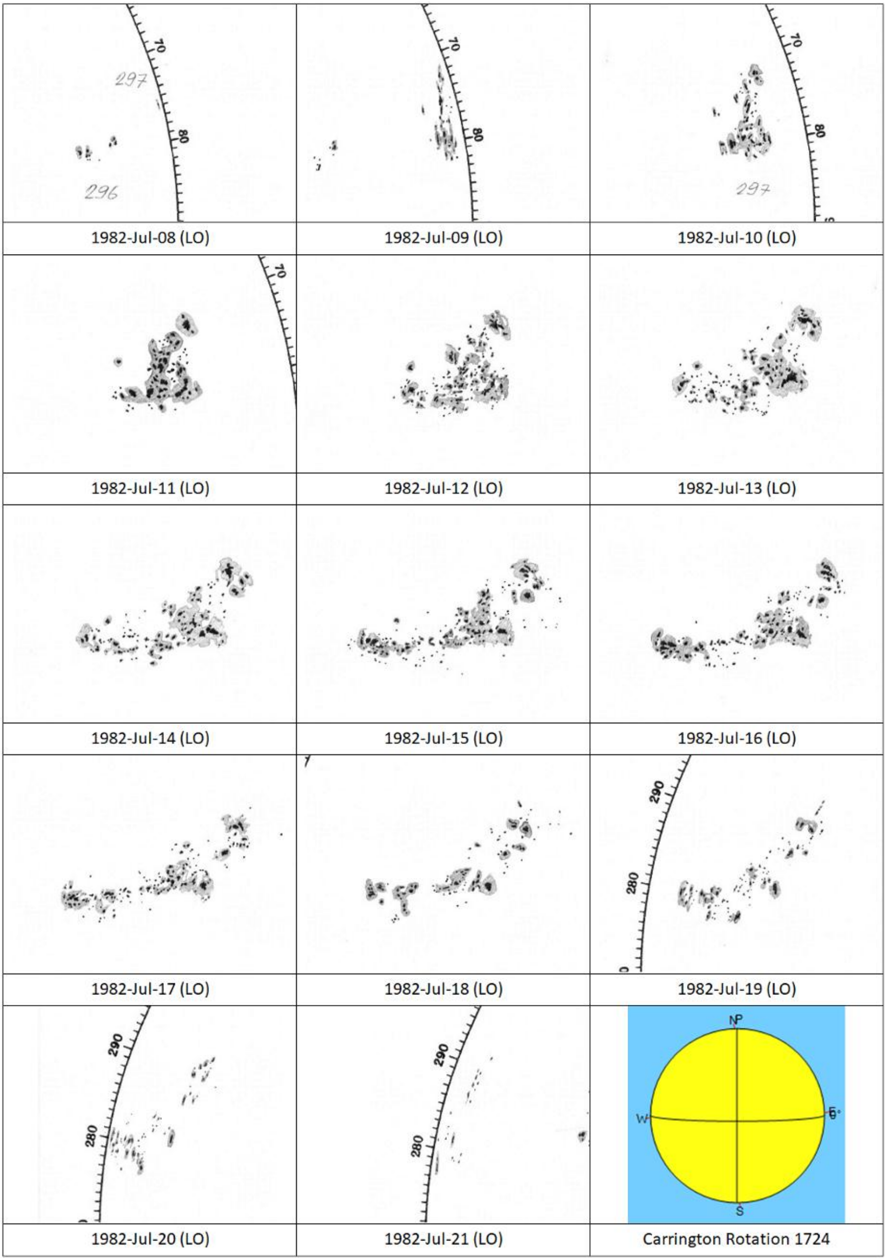


Figure 61. Passage of NOAA Active Region 3804 based on Locarno (LO) Drawings

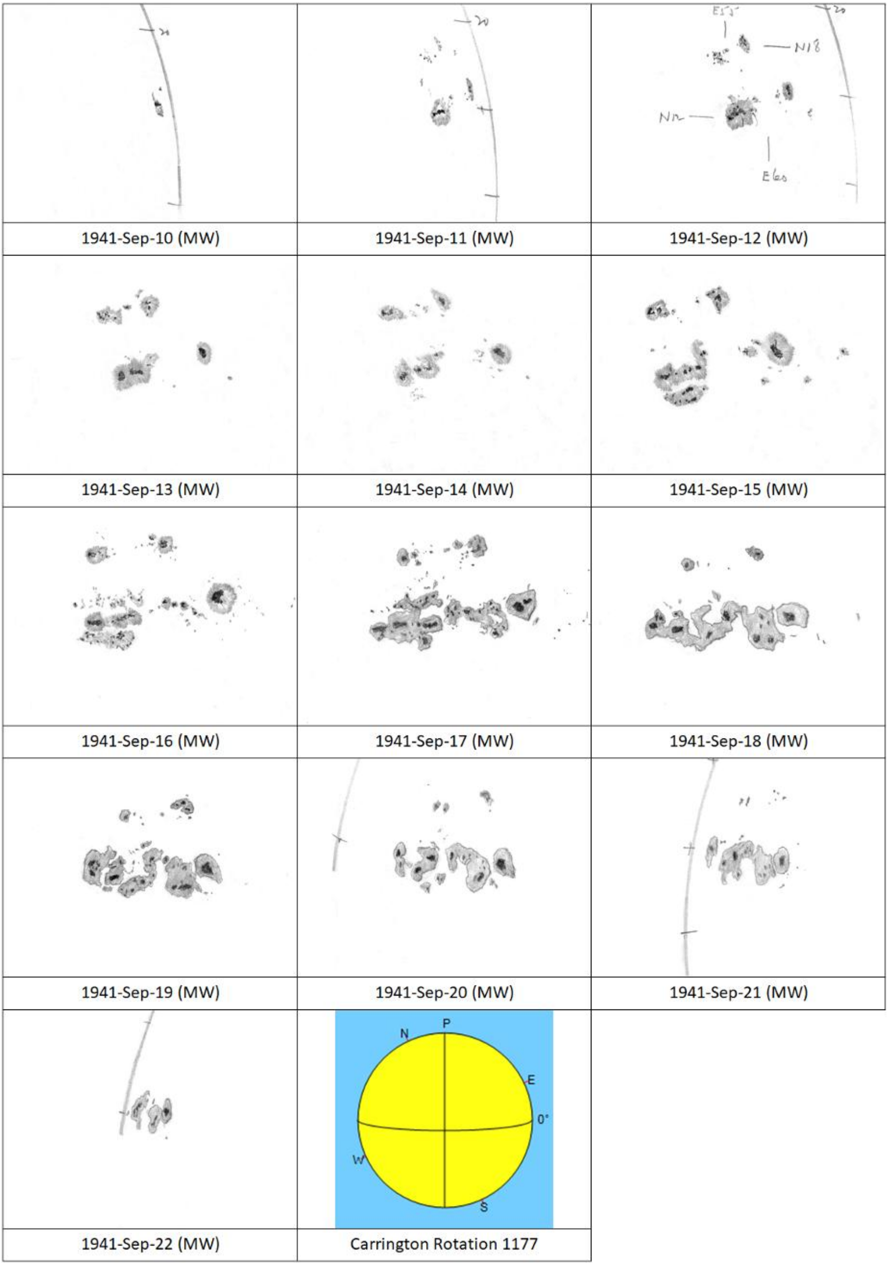


Figure 62. Passage of Greenwich Group 13937 based on Mt Wilson (MW) Drawings

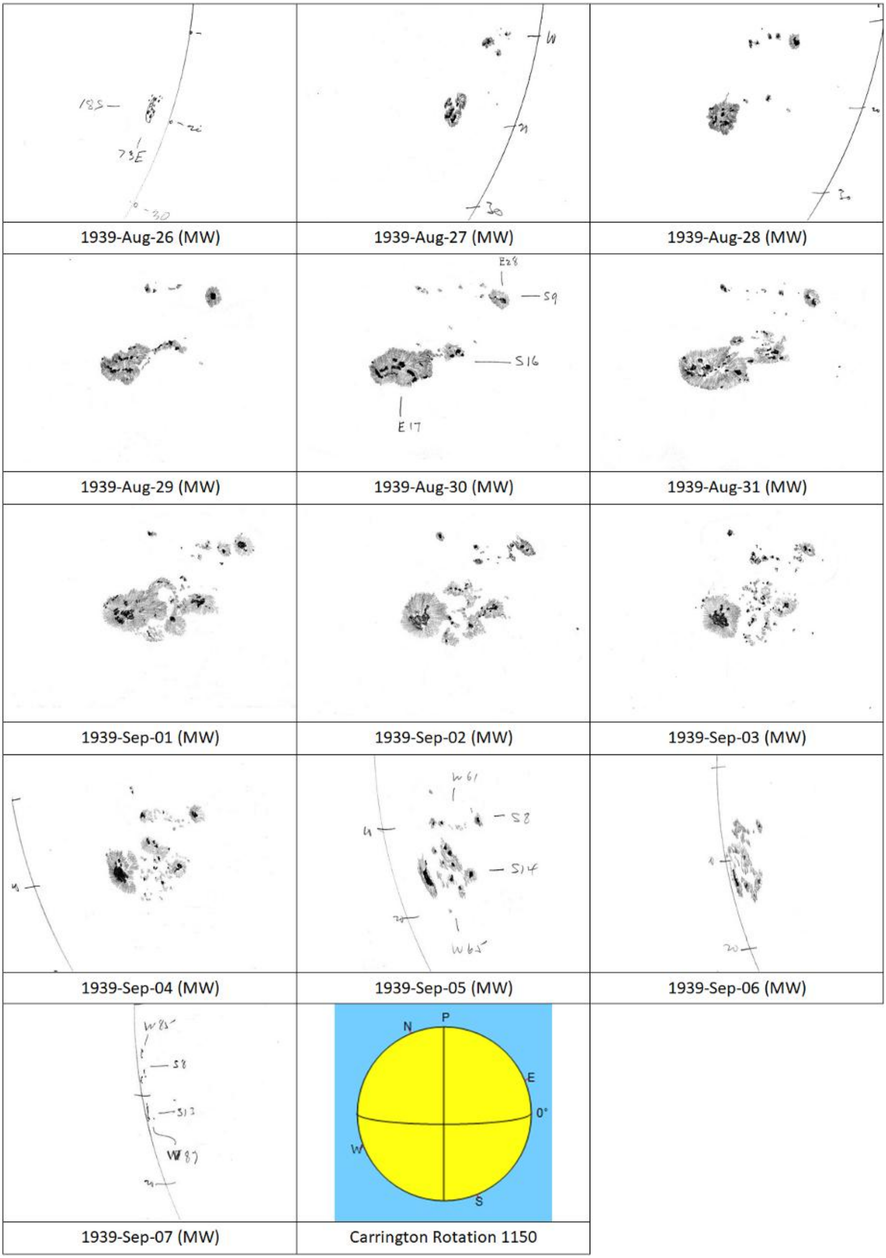


Figure 63. Passage of Greenwich Group 13394 based on Mt Wilson (MW) Drawings

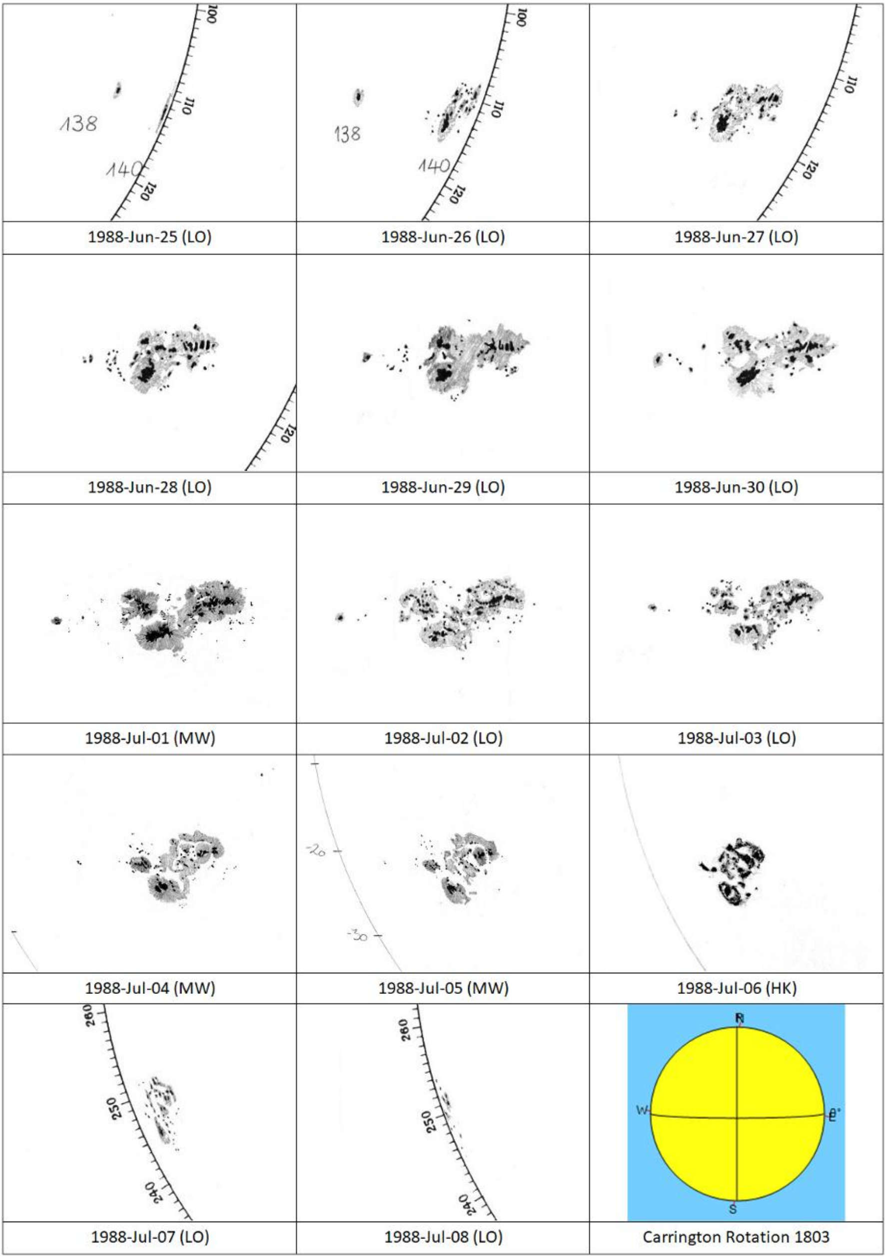


Figure 64. Passage of NOAA Active Region 5060 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

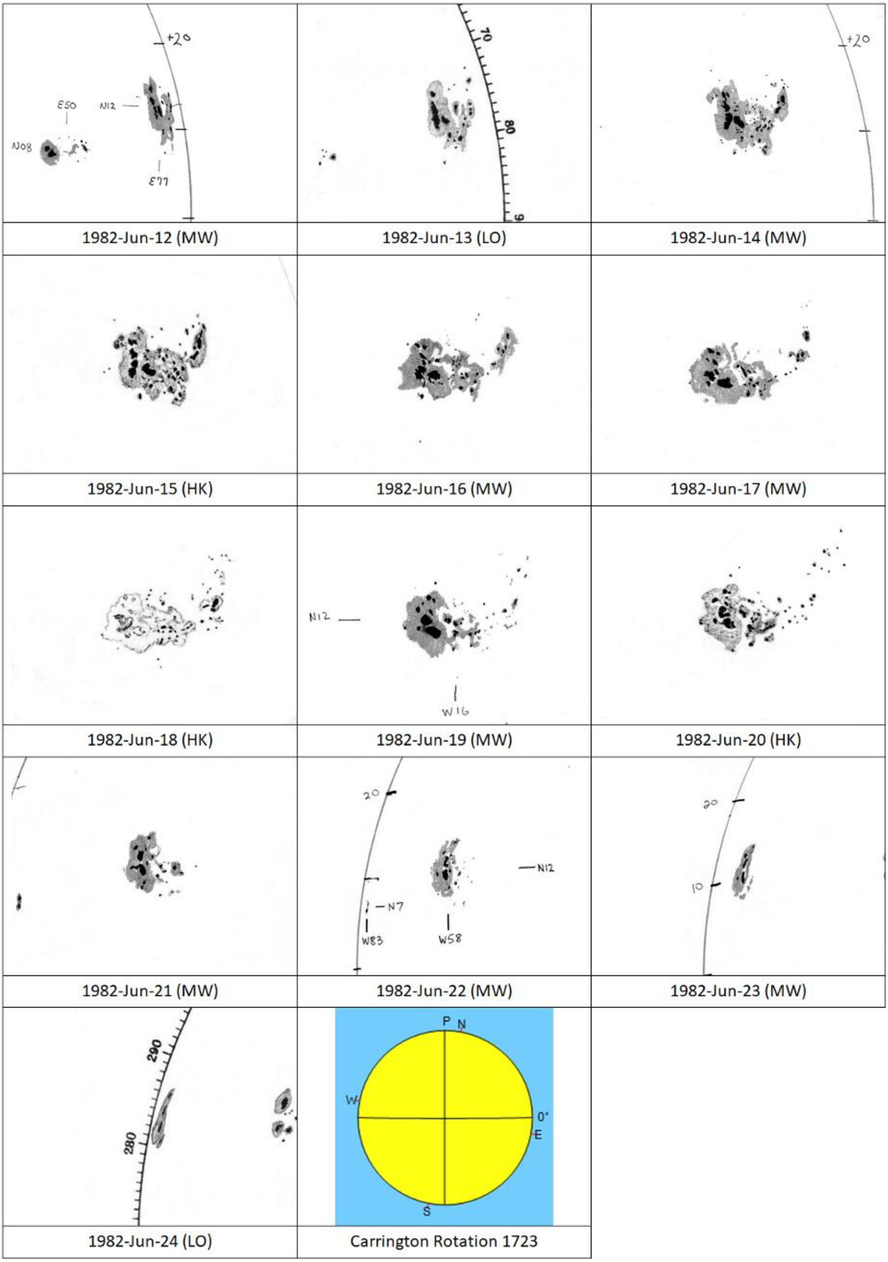


Figure 65. Passage of NOAA Active Region 3776 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

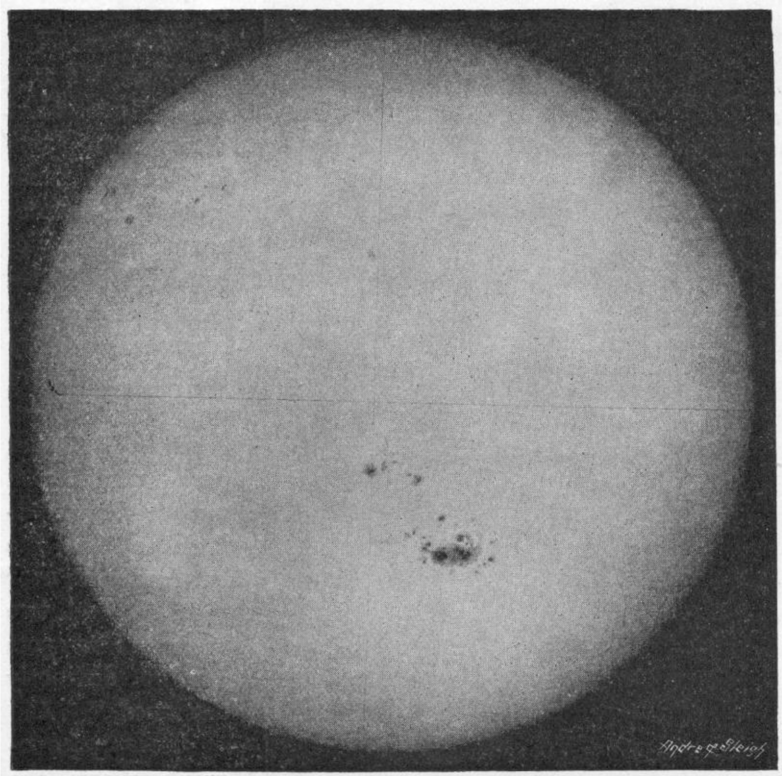


Figure 66a. Greenwich Group 2421. Royal Observatory, Greenwich Photograph 1892 February 13 [28]

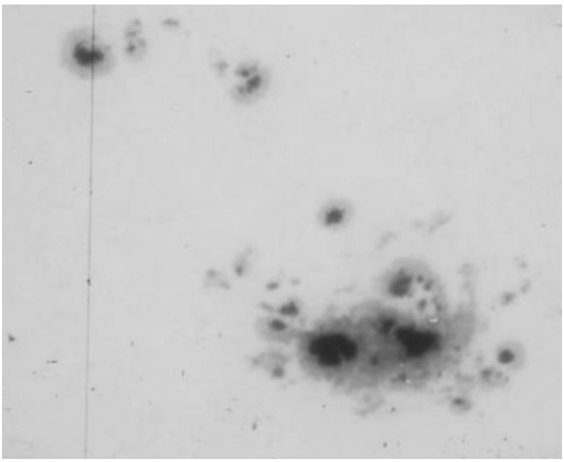


Figure 66b. Greenwich Group 2421. Royal Observatory, Greenwich Photograph 1892 February 13 [24]

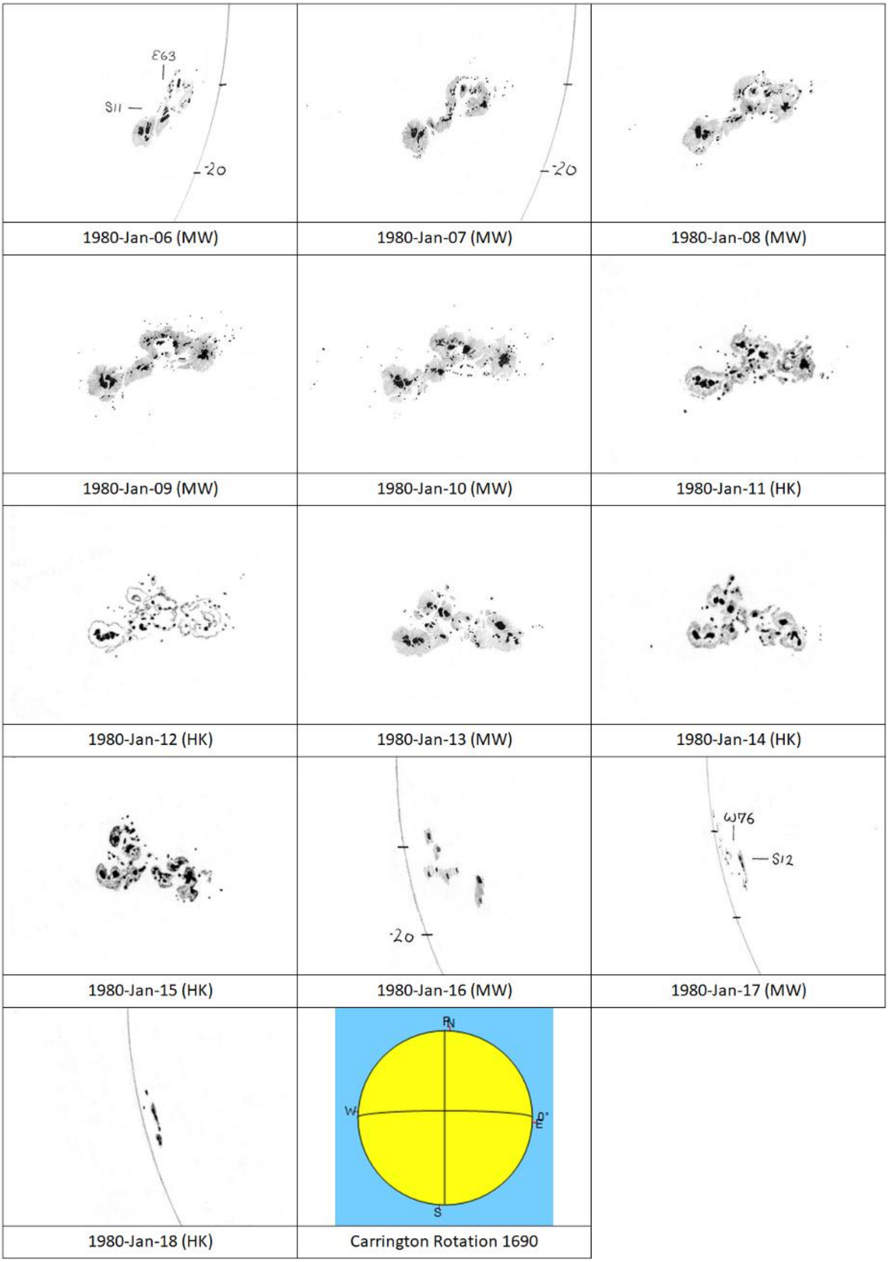


Figure 67. Passage of NOAA Active Region 2779 based on Mt Wilson (MW), Hisako Koyama (HK) and Locarno (LO) Drawings

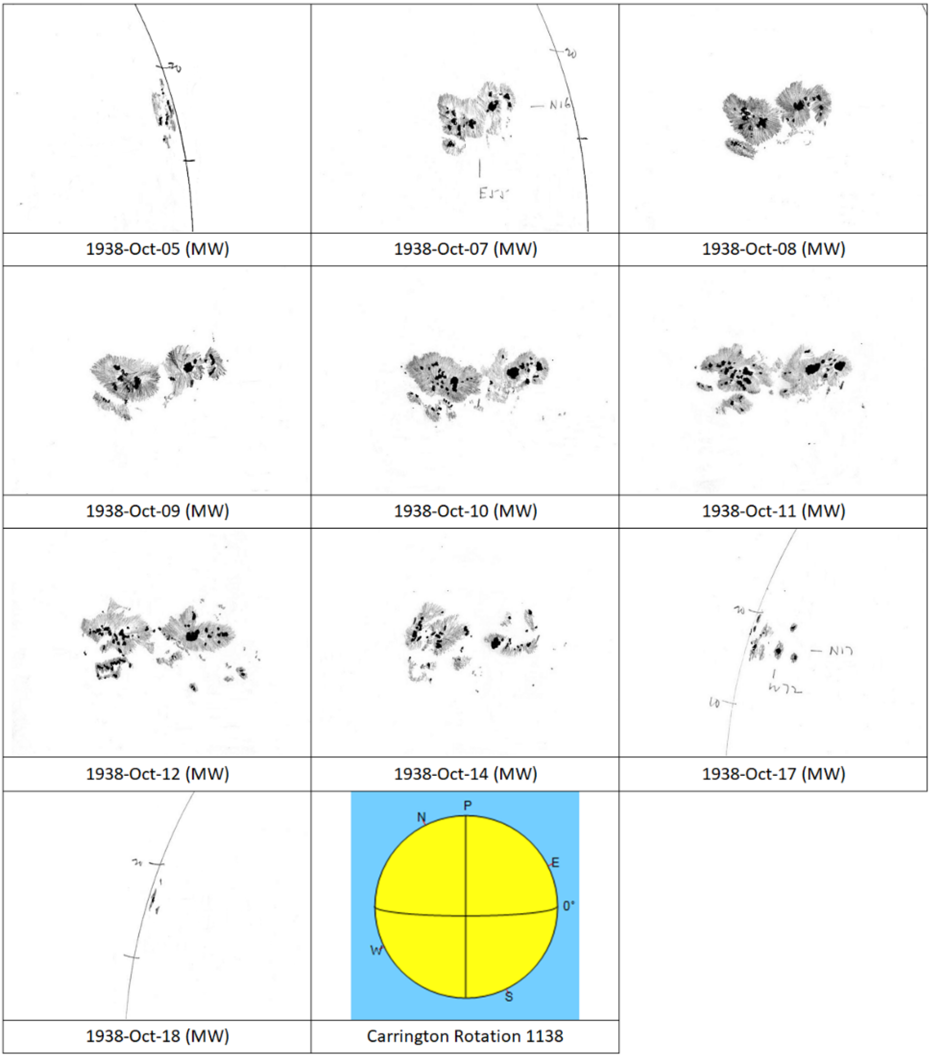


Figure 68. Passage of Greenwich Group 13024 based on Mt Wilson (MW) Drawings

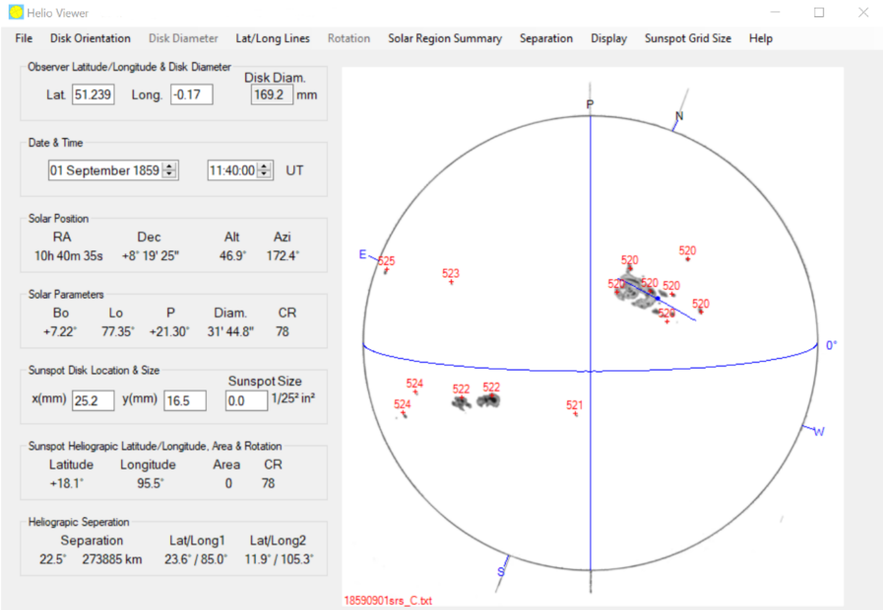


Figure 69a. Carrington Drawing from 1859 September 1 imported into HelioViewer [19] (Carrington's group numbers superimposed)

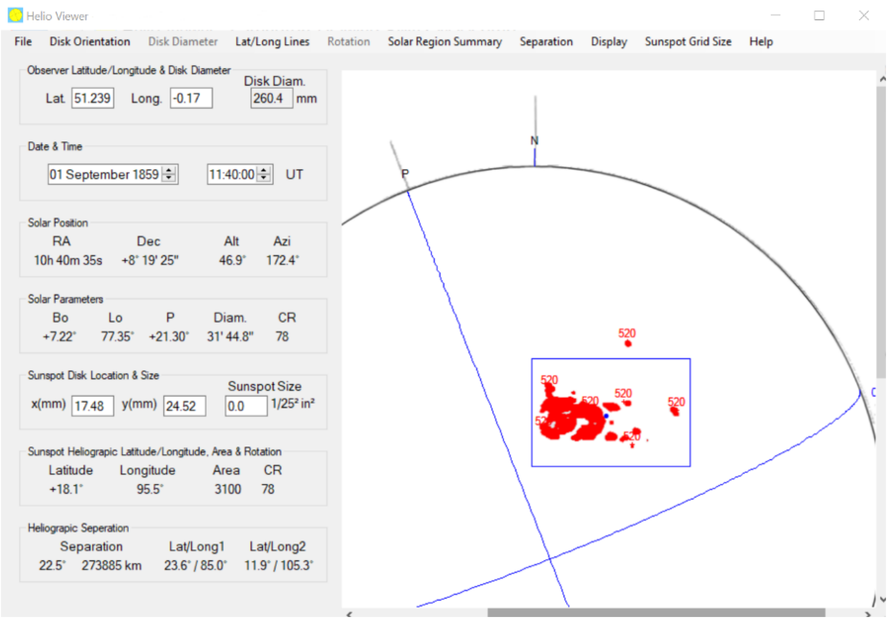


Figure 69b. Area of the Carrington Event Sunspot Group

Acknowledgements

This book includes sunspot drawing from the the 150-Foot Solar Tower of the Mt. Wilson Observatory. This is operated by UCLA, with funding from NASA, ONR and NSF, under agreement with the Mt. Wilson Institute. The National Museum of Nature and Science, Tokyo, Japan is acknowledged for providing reproductions of Ms. Koyama’s sunspot drawings. The Locarno sunspot drawings from the Specola Solare Ticinese, Locarno, Switzerland are also acknowledged. The Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager (HMI) Continuum images are Courtesy of NASA/SDO and the HMI science team. Finally, the International Sunspot Number data used in this book is courtesy of Sunspot Index and Long-term Solar Observations (SILSO), Royal Observatory of Belgium, Brussels.

Astronomical Societies

Although observing the Sun, or indeed any other astronomical object, by oneself is satisfying and of interest, more can be gained by combining observations with other observers. In the UK there are two national amateur astronomical organisations where your observations can be submitted on a monthly basis – the Society for Popular Astronomy [33] and the British Astronomical Association [34]. As these organisations have observers based in many locations around the world, gaps in observing due to the weather can be mitigated thus enabling the monitoring of solar activity on every day. It is also of interest to see what other observers are submitting in terms of observations and images. Both organisations show solar observations on their website and in their publications. Many local astronomical societies include active solar observers (it is also worth visiting your local society before purchasing any equipment for solar observing – societies will often have dedicated solar observing sessions that are open to all). The Federation of Astronomical Societies [35] gives a list of local societies in the UK. Other countries often have similar national organisations (e.g. the American Association of Variable Star Observers [36]) as well as numerous local astronomical societies.

Figure Credits

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The cover image shows from top to bottom the great sunspots from 1947 March (HK), 1946 February (MW), 2014 October (MW), 1947 April (HK), 1989 March (MW), 1946 July (MW) and 1951 May (MW).

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Appendix A – The Occurrence of the Great Groups within Cycles

The five greatest sunspot groups all occurred in Cycle 18. This Cycle was the third strongest solar cycle of the 20th century based on the peak smoothed International Sunspot Number [37] (after Cycle 19 peaking in early 1958 and Cycle 21 peaking in late 1979). It began in 1944 February, peaked in 1947 May with a smoothed International sunspot number of 219 and ended in 1954 April. Figure 70 (top left) shows in blue the monthly International Sunspot Number [37] while the red curve is the smoothed RI Sunspot Number. Finally, the green vertical lines are the dates of the five great sunspot groups – note that two of these occurred on the rise to maximum, two close to maximum and one on the latter part of the declining phase. This distribution of large sunspots within a cycle is unusual – Appendix B shows that two-thirds of large sunspot groups occur after rather than before sunspot maximum.

Also shown in Figure 70 are similar graphs for the occurrence of the 1989 great sunspot in Cycle 22 (at the first peak of the cycle) and the 2014 great sunspot in Cycle 24 (just after the second peak).

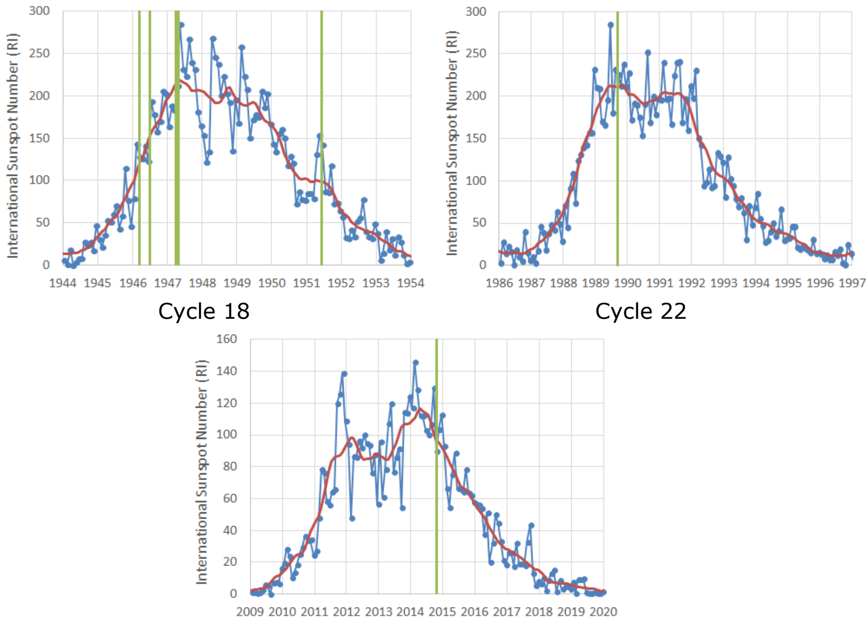

Figure 70. The Occurrence of the Seven Great Sunspot Groups within Solar Cycles

Appendix B - Distribution of Sunspot Groups within Cycles

The Royal Greenwich Photoheliographic Results (GPR) sunspot catalogue and Debrecen Photoheliographic Data [2] has been used to assess when large sunspot groups appear during solar Cycle 12 (1878) onwards. Figure 71 shows a histogram of groups with areas greater than or equal to 1000 MSH relative to the peak of cycles as a percentage of the cycle length. The start and end of each cycle has been determined using the minimum smoothed International Sunspot Number [37] and 0% is at the cycle peak. This shows a skewed distribution with two-thirds of groups (67%) with areas ≥ 1000 MSH appearing after solar maximum.

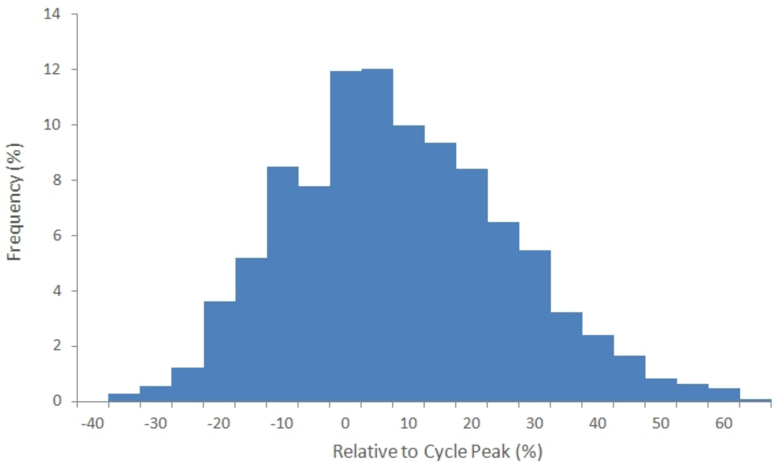

Figure 71. Frequency (%) of Groups with area ≥ 1000 MSH relative to Cycle Peak

It is also useful to consider the difference in the number of large groups between cycles. This is shown in Figure 72 again for groups with areas ≥ 1000 MSH where the Cycle Sunspot Number (Appendix C) has been used to assess the relative strength of cycles. The line is a linear fit to the data. This figure shows that Cycle 18 does not have an unusually high number of ≥ 1000 MSH groups for the strength of this cycle. It did have the highest number of groups with areas ≥ 2000 MSH at 18 with Cycles 17 and 19 having 17 such groups each). Note that Cycle 24 had the second lowest number of groups with areas ≥ 1000 MSH after Cycle 14.

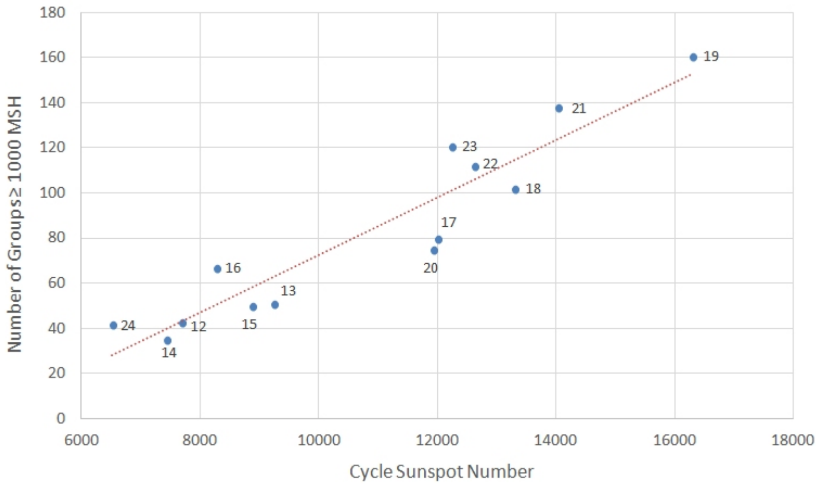

Figure 72. Number of Groups with area ≥ 1000 MSH compared with the Cycle Sunspot Number

Appendix C - Cycle Sunspot Number

The relative strength of sunspot cycles is usually assessed by comparing the maximum smoothed International Sunspot Number (RI) (e.g. [38]) of each cycle (Cycle 1 peaked in 1761 June). Although the smoothed RI is a 13-month average, it does not necessarily indicate the strength of the whole cycle as not all cycles are of the same duration and/or of a similar shape as is shown in Figure 73. The time in cycle is relative to the average date between the minima at the start of a cycle and the end of the cycle (when the smoothed RI is at its smallest). The normalised sunspot number is simply RI divided by the maximum RI of that cycle and is used to show the relative shape between cycles. The duration of cycles is between 9.0 and 13.6 years while some cycles have just one peak while others are double peaked. Figure 73 also shows that the shape of some of the earlier cycles are quite different and variable compared to Cycles 14 to 24 (i.e. from the early part of the 20th century to the present).

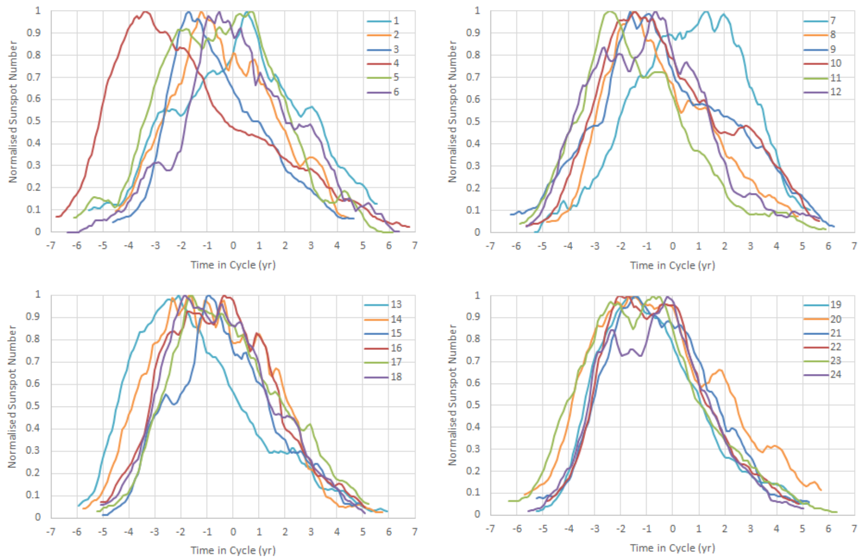

Figure 73. Cycle shape and duration based on a normalised Smoothed Sunspot Number

Perhaps a better measure of the strength of a cycle is a Cycle Sunspot Number based on RI. This is simply the sum of the monthly RI between the minimum at the start of a cycle and the minimum at the end of a cycle.

Figure 74 shows a comparison of the maximum smoothed RI and the Cycle RI for each complete solar cycle since 1750 (the red line is a linear fit to the data). Table 10 show the solar cycles based respectively on the maximum and Cycle RI. These show that Cycle 19, peaking in 1958, and the largest cycle based on the smoothed RI becomes the second largest using the Cycle RI. The largest Cycle RI cycle becomes Cycle 4 peaking in 1788. Cycle 18 moves from 8th largest to 5th largest while Cycle 24 changes from being the smallest cycle since Cycle 14, peaking in 1906, to the smallest since Cycle 5 peaking a hundred years earlier in 1805.

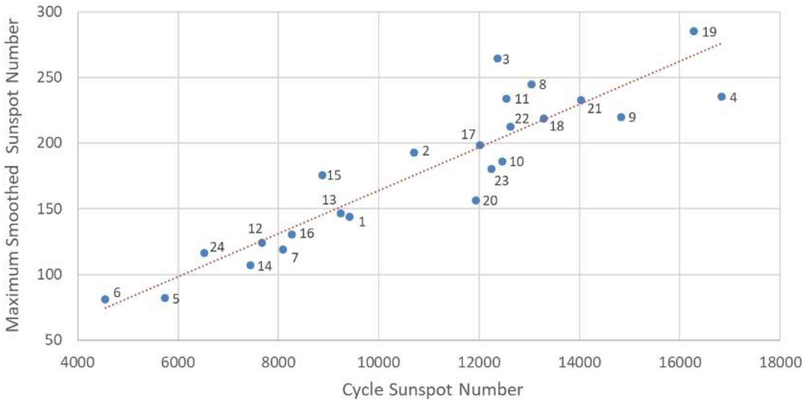

Figure 74. Comparison of Maximum Smoothed Sunspot Number and Cycle Sunspot Number

Cycle	Peak Date	Max SRI	Cycle	Peak Date	Cycle RI
19	1958 Mar	285	4	1788 Feb	16836
3	1778 May	264	19	1958 Mar	16273
8	1837 Mar	245	9	1848 Feb	14829
4	1788 Feb	235	21	1979 Dec	14035
11	1870 Aug	234	18	1947 May	13288
21	1979 Dec	233	8	1837 Mar	13038
9	1848 Feb	220	22	1989 Nov	12620
18	1947 May	219	11	1870 Aug	12544
22	1989 Nov	213	10	1860 Feb	12460
17	1937 Apr	199	3	1778 May	12362
2	1769 Sep	193	23	2001 Nov	12246
10	1860 Feb	186	17	1937 Apr	12010
23	2001 Nov	180	20	1968 Nov	11933
15	1917 Aug	176	2	1769 Sep	10707

Cycle	Peak Date	Max SRI	Cycle	Peak Date	Cycle RI
20	1968 Nov	157	1	1761 Jun	9421
13	1894 Jan	147	13	1894 Jan	9237
1	1761 Jun	144	15	1917 Aug	8874
16	1928 Apr	130	16	1928 Apr	8271
12	1883 Dec	124	7	1829 Nov	7956
7	1829 Nov	119	12	1883 Dec	7675
24	2014 Apr	116	14	1906 Feb	7437
14	1906 Feb	107	24	2014 Apr	6531
5	1805 Feb	82	5	1805 Feb	5688
6	1816 May	81	6	1816 May	4701

Table 10. Sunspot Cycles based on Maximum Smoothed International Sunspot Number (left) and Cycle Sunspot Number (right)

Appendix D - Mt Wilson Sunspot Drawings

Daily sunspot drawings have been made since 1917 using the 150-Foot Solar Tower at Mt Wilson Observatory near Los Angeles, USA [8]. The drawings are made using pencil on acid-free paper with a disk diameter of approximately 40cm - these are available online to download as jpg file of approximate size 2400 by 1400 pixels [39]. The solar disk is orientated with the rotation axis vertical, east towards the right and west towards the left. This disk is only shown for sunspot latitudes of approximately 35°N to 35°S. Various information is added to the drawing including a group number and in many cases the magnetic field strength (for complex groups several parts of the group are marked).

These drawings have been used to measure properties of the great sunspot groups (position, longitude extent and area) as well as showing the daily changes in their appearance. To enable the heliographic latitude & longitude and area to be measured, the drawing images have been modified to enable them to be input into Helio Viewer software [19]. The steps to create the Helio Viewer input images are:

- Apply a gamma correction of 0.5 to increase the drawing contrast.
- Rotate the drawing to ensure the rotation axis is vertical (usually by < 1°).
- Reduce the image size by ~35% to give a disk diameter of ~800 pixels (to ensure that the full disk is displayed when read into Helio Viewer).
- Apply a sharpening filter, especially if a rotation has been applied.
- Add a border around the drawing of 200 pixels at the top & bottom and 100 pixels at the left and right.
- Manually add a black circle of 1 pixel width to form the edge of the disk – the middle of the disk is marked on the drawings as a small triangle. The circle will need to fit over the portion of the disk edge of the drawing (a few attempts may be required to ensure a good fit between the circle and the drawing edge).
- Remove any text or makings from the outside of the circle to ensure that Helio Viewer detects the disk edge (sometimes it may also be necessary to clean the inside of the disk)
- Save to bmp, jpg or png format for input into Helio Viewer.

Figure 75 shows an example of the original drawing and a modified version for input into Helio Viewer.

To show the daily change in appearance, the disk drawings have a gamma correction of 0.5 applied and annotation removed. For the pencil lines indicating the location of the magnetic field strength that are within the sunspot penumbra, the Photoshop Clone Stamp tool has been used to remove the lines as is shown in Figure 76.

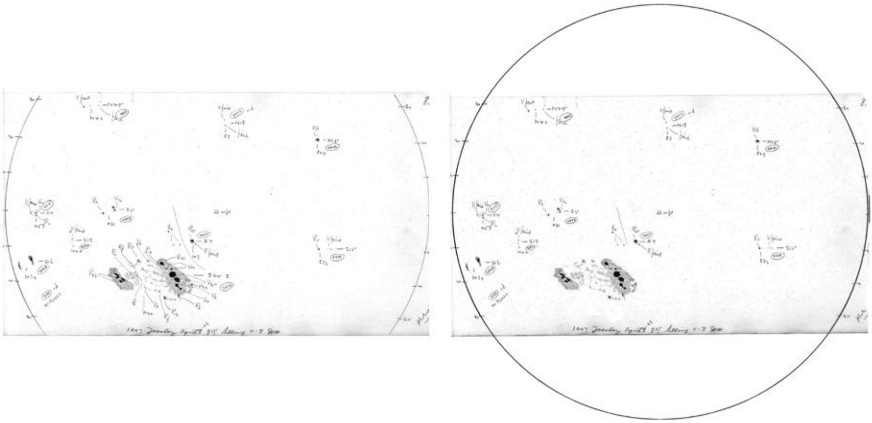

Figure 75. Original and Modified Mt Wilson Drawing from 1947 April 8, 16:15 UT

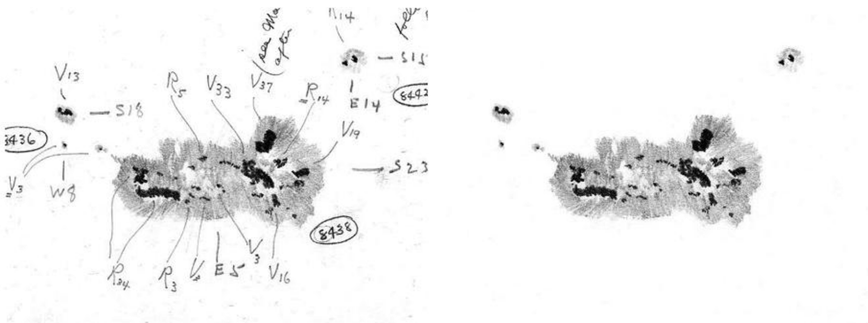

Figure 76. Original and Modified Mt Wilson Group Drawing from 1947 March 9, 20:50 UT

Appendix E - Hisako Koyama Sunspot Drawings

Hisako Koyama (1916 – 1997) worked at the National Museum of Nature and Science (NMNS), Tokyo, Japan where she made solar drawings using a 20cm refractor located in a dome on the roof. She made some 10,000 full disk drawings with this telescope and a 30cm diameter projected disk for over 50 years from 1947 to 1991 even though she had retired in 1981 March. Additional, earlier drawings were made in late 1945 and 1946 with a much smaller telescope and with the 20cm refractor but with a 10cm projected disk. She also made disk drawings with a 15cm refractor from 1989 to 1996 [9], [10].

The NMNS have made Hisako Koyama's drawings from 1947 January onwards available online [40] together with information about each observation (time, seeing and notes) and measurements that have been deduced from the drawings such as number of groups and relative sunspot number. The scanned drawings themselves are available in two sizes: one with a disk diameter of approximately 880 pixels (named s1k_jyymmdd.jpg) and the other twice the size (s2k_jyymmdd.jpg).

As for the Mt Wilson drawings (Appendix D), those by Hisako Koyama (HK) have been used to measure properties of the great sunspot groups as well as showing the daily changes in their appearance. Unlike the Mt Wilson drawings, the HK drawings are orientated east-west in the horizontal direction and north-south in the vertical direction (rather than the rotation axis being in the vertical direction). The following steps have been applied to enable the HK drawings to be input into Helio Viewer [19] using the smaller s1k_jyymmdd.jpg drawings:

- Remove as much of the background as possible (without removing the sunspot penumbra) – the RegiStax [41] histogram function has been used.
- Rotate the drawing by the rotation position angle (P) to ensure the rotation axis is vertical – an additional rotation is required (usually by < 1°).
- Manually add a black circle of 1 pixel width to form the edge of the disk – the middle of the disk is marked on the drawings and the circle will need to fit over the existing disk edge.
- Remove any text or makings from the outside of the circle to ensure that Helio Viewer detects the disk edge (sometimes it may also be necessary to clean the inside of the disk)
- Save to bmp, jpg or png format for input into Helio Viewer.

Figure 77 shows an example of the original drawing and a modified version for input into Helio Viewer (this drawing a just a few hours after the full disk image shown in Figure 75).

To show the daily change in appearance, the larger disk drawings have been used together with background removal (again using RegiStax).

The example shown in Figure 78 is just a few hours after than from Mt Wilson in Figure 76 – note the difference in details in the KH drawing, especially for umbrae, small sunspots and pores.

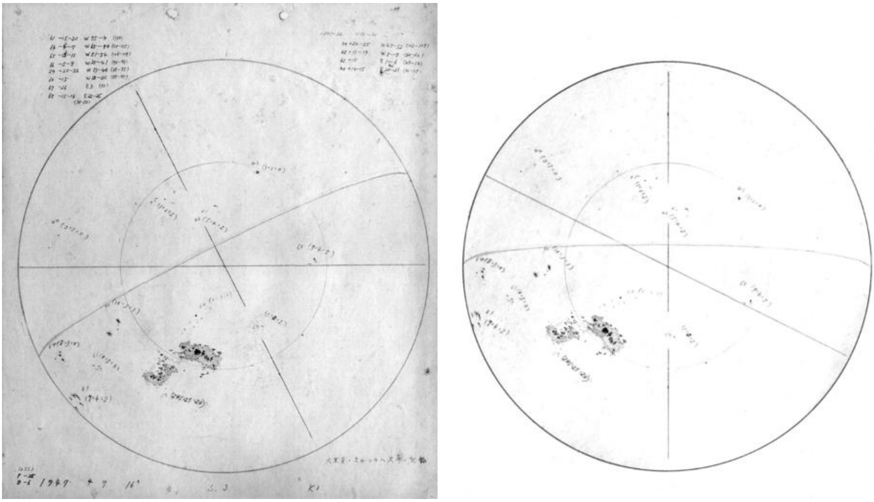

Figure 77. Original and Modified Hisako Koyama Drawing from 1947 April 9, 07:00 UT

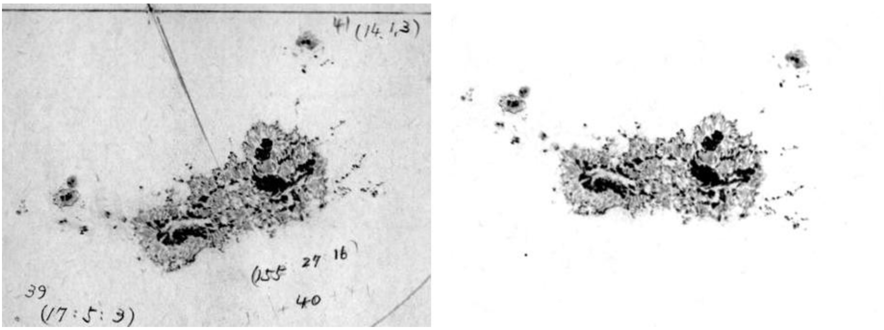

Figure 78. Original and Modified Hisako Koyama Group Drawing from 1947 March 10, 01:30 UT

Appendix F - Differential Rotation

The identification of the same group on successive rotations of the Sun relies on the measured longitude of the group. Heliographic longitude is measured assuming a fixed rotation period, known as the Carrington rotation period, which has a sidereal rotation rate of 25.38 days [31]. The synodic rotation period varies slightly throughout the year due to the eccentricity of the Earth's orbit and inclination of the Sun's rotation axis [42]: a mean synodic period of 27.2753 days is used for calculating Carrington longitudes.

As the Sun is not a solid body, the actual rotation period varies with latitude due to differential rotation. The Sun rotates fastest at the equator and slower at high latitudes above and below the solar equator. The equation to describe the differential rotation rate is given by:

$$\omega = A + B \sin^2(\phi) + C \sin^4(\phi)$$

where ω is the daily sidereal rate in degree per day, ϕ is the solar latitude and A, B and C are constants (degree per day). Four sets of constants based on various studies are given in Table 11. The difference in the longitude over one synodic rotation due to differential rotation is shown Figure 79. This shows that the differential rotation rate is greater than Carrington rotation rate at the equator than at higher latitudes (as expected). It also shows that the differential and Carrington rates are the same at close to latitudes of ±15° for the Abetti and Newton & Nunn studies, at ±20.6° for the Stix study and at ±26.1° for the Snodgrass study (based on Doppler rather than sunspot data). Note that the Helio software programs [19] use the Maunder differential rotation rate constants.

	A (°/day)	**B (°/day)**	**C (°/day)**	**Comments**	**Ref.**
Maunder	14.37	-2.60	0.00	Based on small isolated sunspot from 1888-1893	[43]
Newton & Nunn	14.38	-2.96	0.00	Based on single recurrent sunspots from 1934-1944	[44]
Stix	14.54	-2.86	0.00	Average of Greenwich (1874-1976) all spots & Mt Wilson (1921-1982) all spots	[45]
Snodgrass & Ulrich	14.71	-2.39	-1.78	Based on Mount Wilson Doppler observations from 1967 to 1987	[46]

Table 11. Differential Solar Rotation Rates

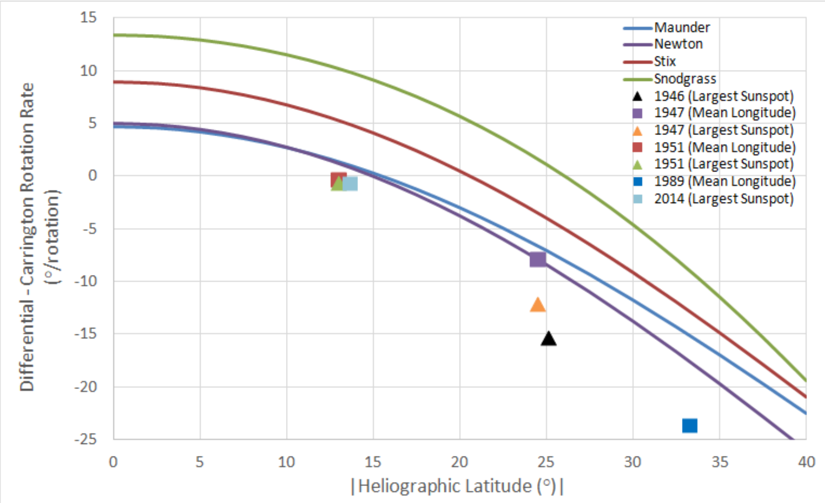

Figure 79. Difference in the longitude over one synodic rotation due to differential rotation

The heliographic longitude of the centre of the disk, Lo, decreases with time (being 360° at the start of a solar rotation and 0° at the end). Thus, the longitude of a long-lived sunspot on the equator will increase in numerical value from one rotation to the next due to differential rotation. For a high latitude sunspot, its longitude will decrease from one rotation to the next.

The symbols in Figure 79 show the measured longitudinal drift for the seven great sunspot groups. The longitude drift is based on the largest sunspot (triangles) and/or the mean longitude of the group (squares). Exceptions are (i) the first of the four rotations in 1947, which has a different rotational rate compared to the other three rotations (see Figure 25), (ii) the first of the three rotation in 2014 where the main sunspot changes from the following to leading position within the group through the disk passage (see Figure 44) or (iii) where it is clear that the longitude extent of a group has significantly reduced through the decay of leading or following sunspots.

The rotation rates for the 1947 (mean longitude), the 1951 and the 2014 great groups all lie close to the Maunder curve – the 1947 rate based on the longitude of the main sunspot has a lower than expected rotation rate. The 1946 groups also have quite a different rotation rate for any of the differential rotation rates given in Table 11 and shown in Figure 70, due to a large proper motion. The high latitude 1989 group also has a higher rotation rate than given by the Newton rotation model thus indicating a proper motion of more than 5° per rotation.

Appendix G - Comparison of Sunspot Areas

As a comparison, the Mt Wilson & Hisako Koyama disk drawings have been used to calculate the area of the five great sunspot groups in Cycle 18 and compared with the Greenwich areas. The method used to calculate the group areas from the disk drawings is described in Appendix H and I. Results are shown where the angle from the centre of the disk to the group is less than 70° (to avoid errors in the measured area due to foreshortening). Note that for the two great groups in 1946 only the Mt Wilson drawings have been used as the long time-series Koyama drawings with the same telescope and projection disk size only began in 1947 January [9].

Figure 80 shows the Greenwich and Mt Wilson area for group 14417 in 1946 February. The upper pair of curves is for the total group area in MSH while the bottom pair is for the area of all the umbrae within the group. This shows that the Mt Wilson areas generally agree with those from Greenwich for the whole group while for the umbrae from the Mt Wilson drawings gives a reduced area compared to Greenwich. Meanwhile for the 1946 July group, 14585 shown in Figure 81, the Mt Wilson total area is higher than for Greenwich on most days while the umbrae areas are very similar between Greenwich and Mt Wilson.

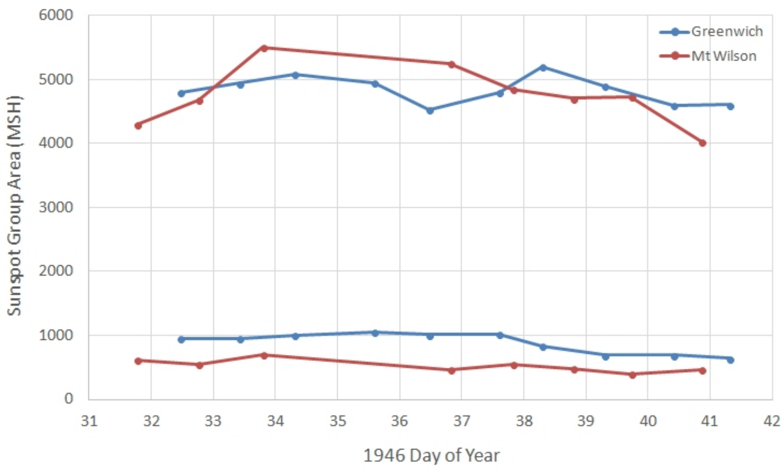

Figure 80. Greenwich and Mt Wilson area for Group 14417 (1946 February)

For the 1947 March group, 14851, shown in Figure 82, there is a good comparison between the three sets of total area measurements for the first part of the group's disk passage. For the second part, the Koyama areas are slightly larger than Greenwich but there is an increase for the

Mt Wilson areas. For umbrae, the Mt Wilson areas are below those of Greenwich and Koyama – comparing Figure 76 and Figure 78 on March 9/10 for Mt Wilson and Koyama respectively shows the greater detail in the Koyama drawing with many more small umbrae and pores surrounding the main sunspot. These would all lead to a larger umbrae area from the Koyama drawings.

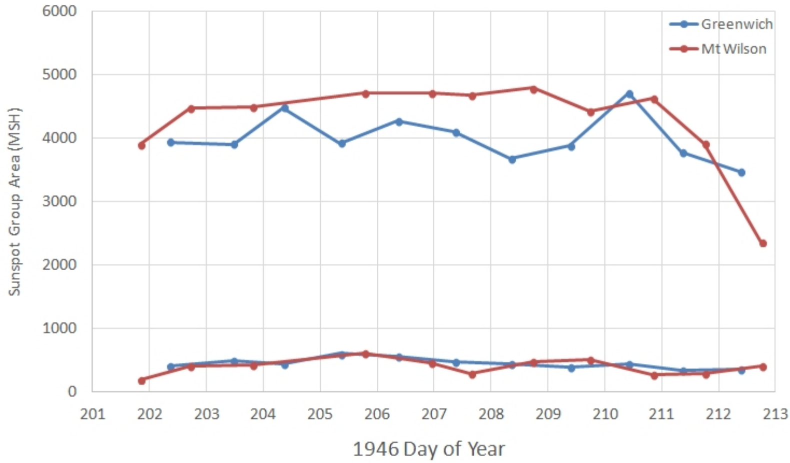

Figure 81. Greenwich and Mt Wilson areas for Group 14585 (1946 July)

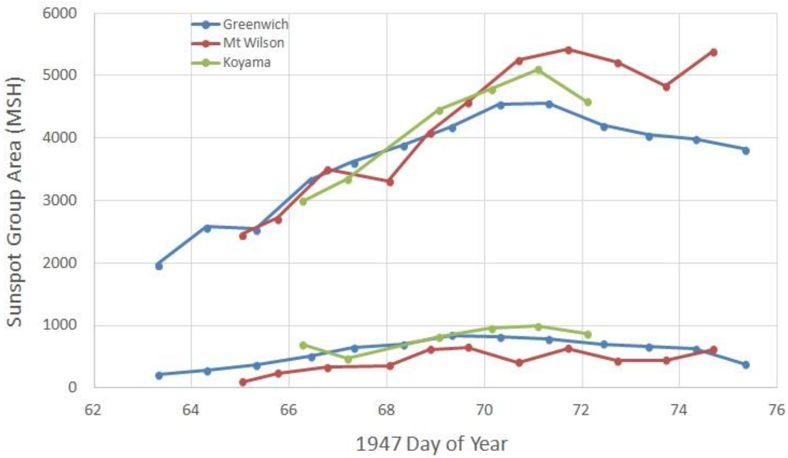

Figure 82. Greenwich, Mt Wilson and Koyama areas for Group 14851 (1947 March)

For the largest sunspot group, 14886 in 1947 April, there is a good overall correspondence in the three total areas as shown in Figure 83. However, there is quite a large day-to-day area variation in total area from the Mt Wilson drawings - this is not present in the Greenwich and Koyama areas. This might be related to the less detailed Mt Wilson drawings compared to the Koyama drawings. Again, the Mt Wilson umbrae areas are slightly less than the Greenwich and Koyama areas.

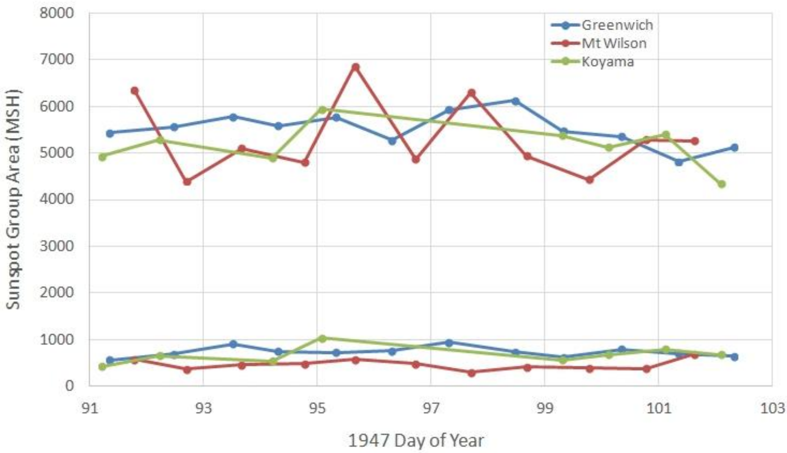

Figure 83. Greenwich, Mt Wilson and Koyama areas for Group 14886 (1947 April)

Figure 84 for the 1951 May great group 16763, there is a good correspondence between the Greenwich and Koyama total areas with the possible exception at the start and end of the group's passage. The same is true for the Mt Wilson area for the start of the passage but towards the end of the passage the areas are significantly higher for Mt Wilson. As is shown in Figure 28, this sunspot was quite complex in shape with several penumbral parts that could be difficult to draw accurately. For umbrae there is a good correspondence between Greenwich and Mt Wilson. This is also the case for the Koyama drawings at the start of the group passage but not for the end where the umbrae measurements are significantly higher.

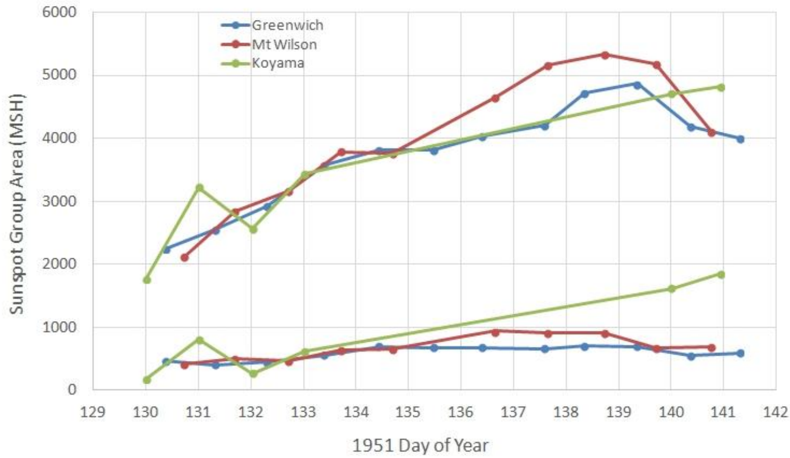

Figure 84. Greenwich, Mt Wilson and Koyama areas for Group 16763 (1951 May)

Appendix H - Calculating Drawing Sunspot Areas

The sunspot area is calculated using the angle, ρ, on the surface of the Sun from the centre of the solar disk to the sunspot as well as the diameter of the drawing [47], [48]. In addition, ρ requires the apparent diameter of the Sun [49].

The basic steps used to calculate the sunspot group area from Mt Wilson and Hisako Koyama drawings are:

- Use a specially written threshold program to assign a red colour to sunspot penumbra and a green colour to umbra as shown, for example, in Figure 85.
- Use another program to calculate the area of each red and green image pixel and sum to give the total group area and the total umbra area as shown in Figure 86.

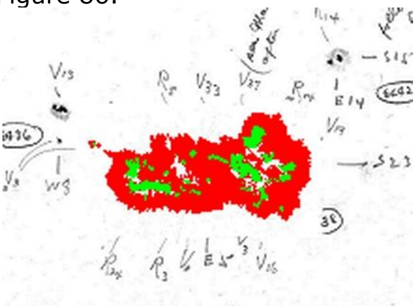

Figure 85. Penumbra and Umbra assigned pixels from 1947 March 9

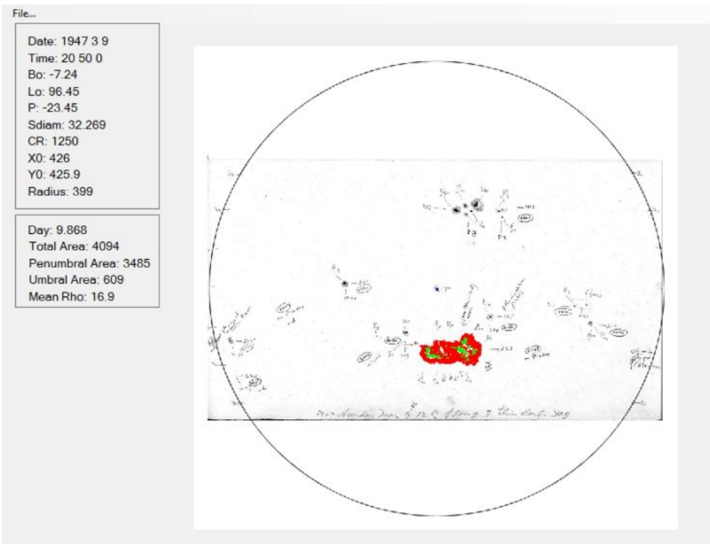

Figure 86. Sunspot area calculation from 1947 March 9

The threshold program requires as input the size of the image solar disk (approximately 800 pixels), the coordinates of the middle of the solar disk and the pixel coordinates of a rectangular box around the group. The program uses pre-defined threshold pixel values to separate the background, penumbra and umbra. Typical threshold values are between 230 and 100 for penumbra and less than 100 for umbra. Although the program correctly assigns penumbra and umbra to the correct colour for most group pixels, some manual assigning is required.

The area program requires the date and time together with various heliographic parameters (mostly for the output display except for the apparent solar diameter) and the same disk size and centre coordinates as the threshold program. The ρ angle is calculated for each group penumbra or umbra pixel (red or green) prior to calculating the area of each red and green pixel. The area of an individual pixel at the centre of the disk for an 800 pixel diameter drawing is approximately 1 MSH. The total area is the sum of each calculated pixel area. The mean ρ angle is also calculated for the whole group.

Appendix I – Description of the Greenwich Solar Micrometer

A description of the micrometer used calculate the area of sunspots from Greenwich photographic plates is given in part of a Memoir of the British Astronomical Association [50]. This indicates that sunspot areas are measured using a diaphragm ruled with squares with sides one hundredth of an inch. Given the photographs have a diameter of 10in, this equates to the equivalent digital scanned photograph of 1000 pixels in diameter.

The 'Description of the Greenwich Solar Micrometer' in [50] is reproduced below.

> The measures of the photographs of the Sun, taken at Greenwich, are made with a large position-micrometer, specially constructed for the purpose. In this micrometer the photograph is held with its film side uppermost on three pillars mounted on a circular metal plate. This plate can be turned through a small angle about the pivot in its circumference by means of a screw and antagonistic spring acting at the opposite extremities of a diameter. The pivot of this plate is mounted on the circumference of another circular plate which can also be turned by screw action about a pivot in its circumference, 900 distant from that of the upper plate, this pivot being mounted on a circular plate with a position circle which rotates about its centre. By this means small movements in two directions at right angles to each other can be readily given to the photograph, which is thus accurately centred with respect to the position circle. When this has been done, a positive eyepiece having at its focus a glass diaphragm, ruled with cross-lines into squares, with sides of one-hundredth of an inch (for measurement of areas) is moved along a slide diametrically across the photograph, the diaphragm being nearly in contact with the photographic film so that parallax is avoided. The distance of a spot or faculae from the centre of the Sun—that is to say, from the centre of rotation of the position circle—is read off by means of a scale and vernier to the tenth of a millimetre (corresponding to one-thousandth of the Sun's radius for photographs having a solar diameter of one decimetre). The position angle is read off on the position-circle which rotates with the photographic plate. (See Figure 87 and Figure 88).

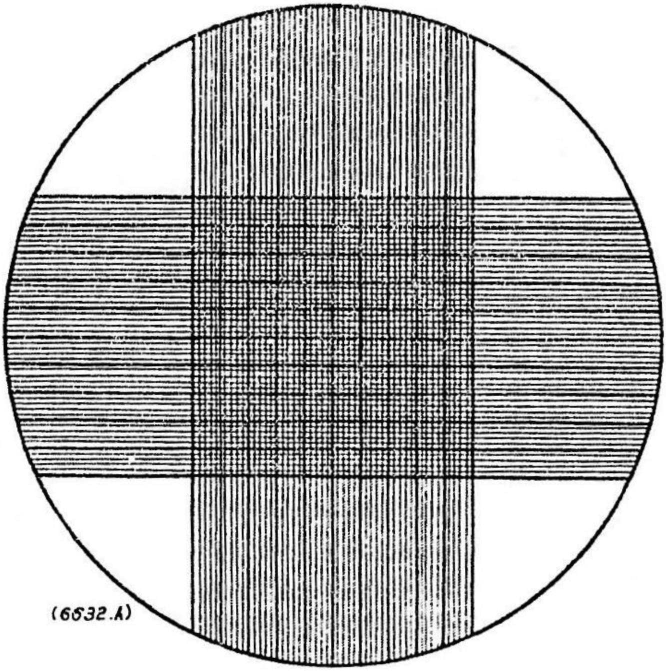

Figure 87. Diaphragm for the Measurement of the Areas of Spots and Faculas.

In measuring a photograph, the image of the Sun is centred as accurately as possible by rotation, the plate being moved by the two tangent screws just mentioned. The position-circle is then set to the reading 0°, and to each 900 therefrom, and the scale readings are taken for both limbs at each of the four settings; the scale is so adjusted that its zero coincides with the centre of rotation of the position-circle, so that the mean of the eight readings for the limb gives the mean radius of the Sun directly.

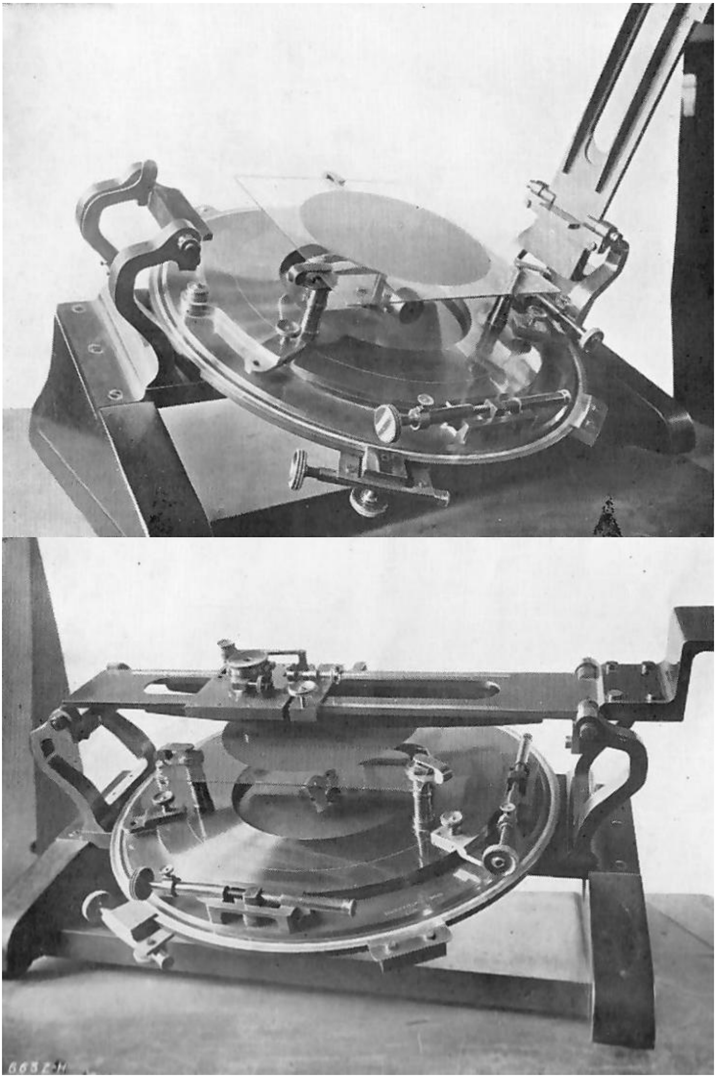
Figure 88. The Greenwich Solar Micrometer (open and shut)

In the principal focus of the photoheliograph are two cross spider-lines (see Figure 89), the images of which appear on every photograph. The position-angles of these cross-lines from the north point of the plate are carefully determined by observations made with the photoheliograph for that special purpose, and, these being known, the actual position-circle readings made with the micrometer on these cross-lines can be at once corrected to true position-angles from the north point. The point, therefore, to which attention is given in placing the photograph in the micrometer is that it is truly centred; the position-angle of the plate does not matter, as in the course of the reduction of the measures the position-angles, as read, are corrected to true position-angles from the north point by applying a correction deduced from the readings of position of the cross-lines. These constants of the radius and position-angle having been determined for the photograph, the magnifier is moved over the plate, the various markings, spots or faculae, are picked up, their positions in distance and angle are read, and the number of squares of the diaphragm which they cover are counted. Two complete sets of measures are made by two separate observers, of whom the one measures with the magnifier on the right of the centre of the instrument and the other measures on the left, the means of the two sets of readings being used in the reduction.

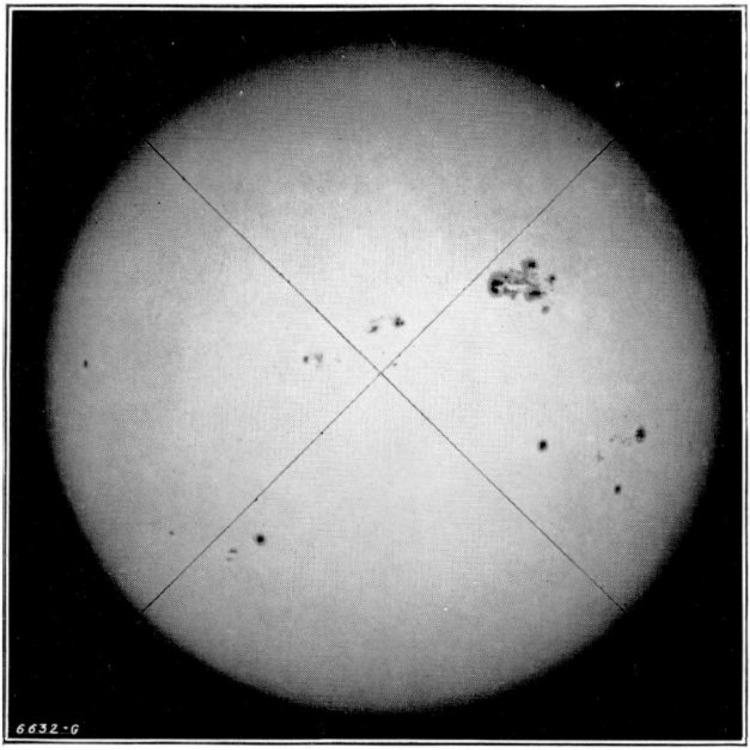

Figure 89. Photograph of the Sun. Taken at Greenwich 1917 August 12d 7h 54m 8s; Greenwich Civil Time. Note the pair of spider-lines crossing the Sun’s disc at right angles to each other.

The description of the method by which the photographs of the Sun are measured has been given in so much detail in order to show, not only that the two measurers work independently of each other, but also that both of them are ignorant of the true position-angles of the objects measured. It is only in the course of the after-reduction that these are ascertained. To the one measurer the part of the circumference of the Sun that he is measuring—the east limb as well as the west—is always on his right hand; to the other measurer it is always on his left hand.

Appendix J - High Latitude Sunspot Groups

The great sunspot group of 1989 occurred at a relatively high latitude of 33°N and towards the peak of Cycle 22 as shown in Figure 70 (Appendix A). Groups at latitudes above and below 30° are relatively rare, are usually small in nature and occur at the start and during the early part of solar cycles. This is illustrated in Figure 90 which shows the latitude of groups for Cycle 22 (based on data from the Debrecen sunspot data [2]) with yellow for groups smaller than 100 MSH, green for groups between 100 MSH and 500 MSH, purple for groups between 500 MSH and 1000 MSH and red for groups greater than 1000 MSH. The 1989 great sunspot is shown as a black dot.

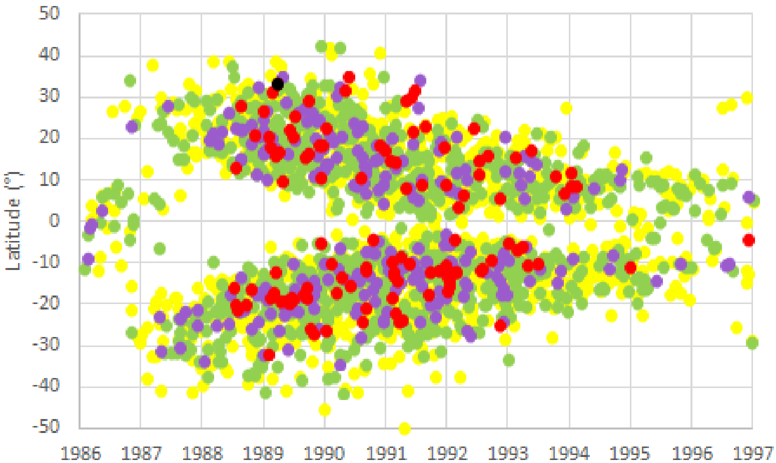

Figure 90. Cycle 22 sunspot group latitudes

Based on the same data source and since 1874, the percentage of groups with a latitude greater than or equal to 30° or less than -30° is 3.45% for all group irrespective of size and just 0.17% for groups with areas greater or equal to 1000 MSH. The distribution of these high latitude groups with latitude and area is shown in Figure 91 and Figure 92. The 1989 great sunspot group is the largest of all the high latitude groups as given in Table 12 for high latitude groups with maximum areas greater than 1500 MSH (the group number is either the Greenwich group number or the NOAA active region number). Also included in the table is the previous rotation of the 1989 group and three other groups from the same cycle.

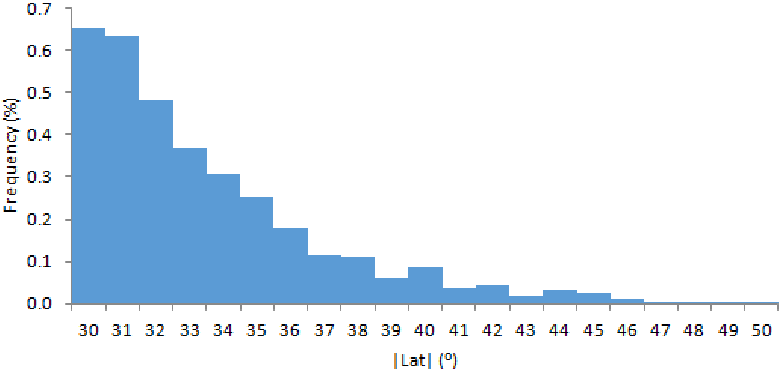

Figure 91. Latitude distribution of high latitude groups above 30°N and below 30°S

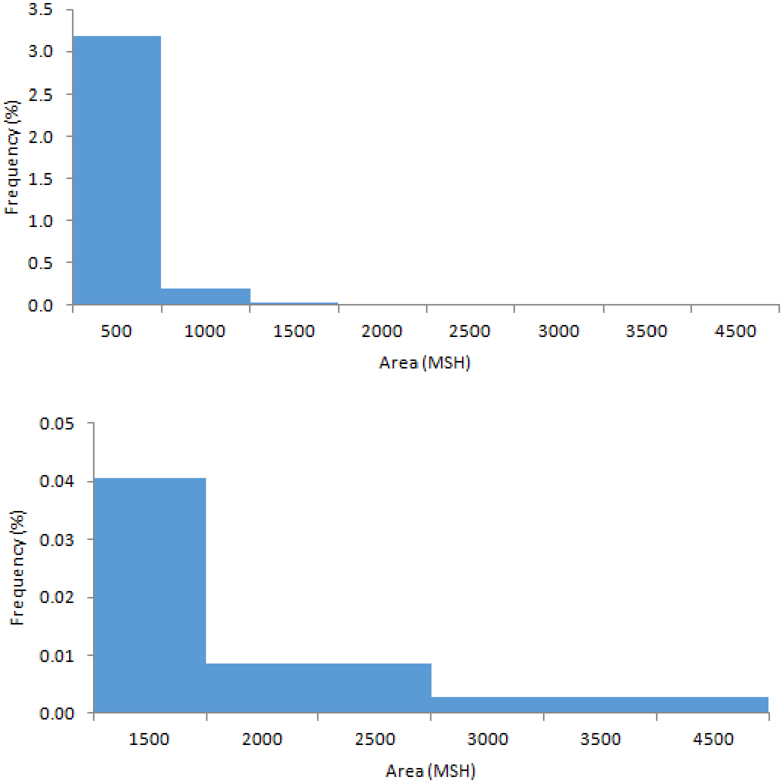

Figure 92. Area distribution of high latitude groups above 30°N and below 30°S (% of all groups)

Date	Group	Area (MSH)	Mean Lat.	Mean Long.
1989 Mar 14	5395	4201	33.4°	255.4°
1937 Jul 28	12455	3303	32.0°	354.2°
1991 Jun 12	6659	2761	31.7°	246.3°
1989 Feb 07	5354	2402	31.6°	282.0°
1989 Jan 15	5312	2364	-31.9°	305.1°
1957 Jun 22	18068	2049	-37.9°	195.5°
1894 Feb 21	3412	1742	-32.1°	186.8°
1990 Apr 15	6022	1648	32.0°	342.1°
1936 Jan 22	11795	1641	-32.1°	133.0°

Table 12. High latitude groups with areas greater than 1500 MSH

Groups above and below 40° represent just 0.28% of all groups (96 groups) – the area distribution is shown in Figure 93. The largest of these groups occurred on 1959 June 11 at 969 MSH as shown in Figure 94 (upper most group at 43°N). Table 13 gives a list of these very high latitude groups with areas greater than 500 MSH. The highest latitude group was seen on 1957 June 22 at 50.3°N.

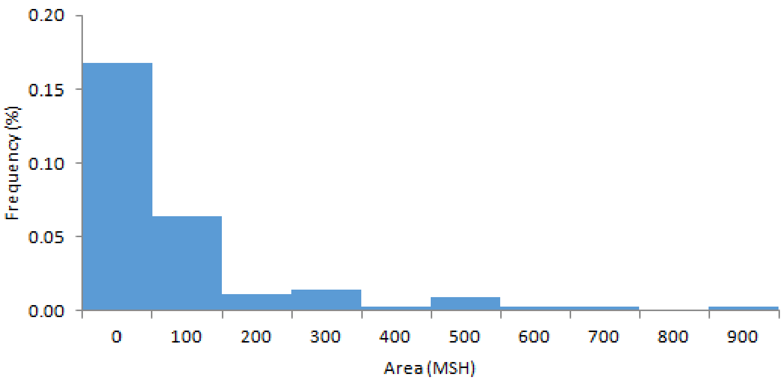

Figure 93. Area distribution of high latitude groups above 40°N and below 40°S (% of all groups)

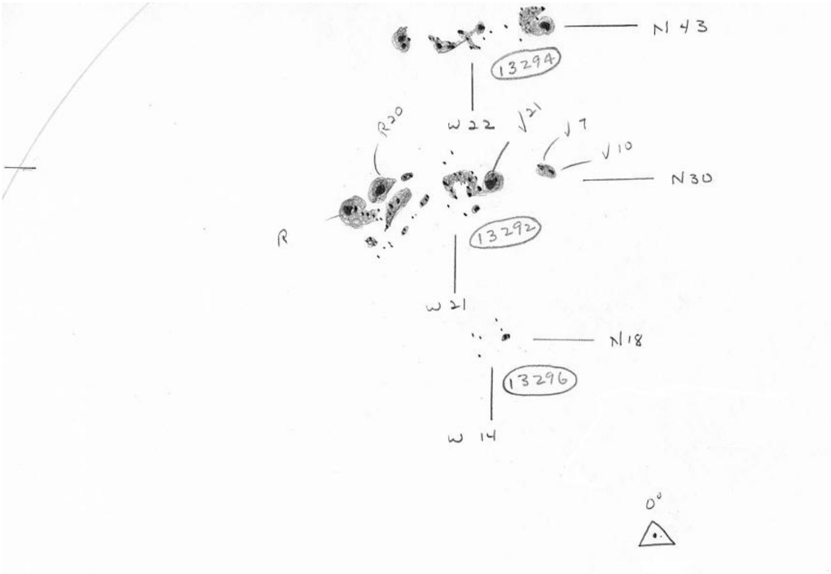

Figure 94. Mt Wilson Group Drawing from 1958 June 11 (NW quadrant)

Date	Group	Area (MSH)	Mean Lat.	Mean Long.
1958 Jun 11	18728	969	43.6°	208.8°
1981 Mar 30	2999	758	-43.3°	102.5°
1958 May 20	18689	620	40.5°	109.2°
1943 May 19	14156	587	-40.9°	166.0°
1977 Feb 12	782	516	-41.4°	162.5°
1959 Oct 03	17656	509	45.2°	115.0°

Table 13. High latitude groups with latitudes above 40°N and below 40°S and areas greater than 500 MSH.

9780957078918