"Sunspot Variation in Latitude, 1861—1902." By WILLIAM J. S. LOCKYER, M.A. (Camb.), Ph.D. (Gött.), F.R.A.S., Chief Assistant, Solar Physics Observatory. Communicated by Sir NORMAN LOCKYER, K.C.B., LL.D., F.R.S. Received January 16, —Read February 11, 1904.

In a previous communication,* Sir Norman Lockyer and I gave the results of a discussion of prominence observations, and pointed out the necessity of dealing individually with small zones on the solar surface.

In that paper brief reference was made to the law of spot zones, as discovered by Carrington, and corroborated by Spörer, and it was further stated that more modern observations had established these *general* deductions of spot distribution. The words "general deductions" were purposely used, as it was then noticed that there were many anomalies that required explanation.

The object of the present paper is to draw attention to these anomalies, and to give the results that have been deduced from a minute examination of the changes of heliographic latitudes of sunspots from year to year. The present evidence indicates that the law of Spörer, although of great importance, represents only a very general idea of a complicated sunspot circulation.

* "Solar Prominence and Spot Circulation, 1872—1901," 'Roy. Soc. Proc.,' vol. 71, p. 446.

From a valuable series of sunspot observations, made between the years 1853 and 1861, Richard Carrington* was the first to point out that spots had a general drift towards the Equator during a sunspot cycle, or, to use his own words, there was indicated "a great contraction of the limiting parallels between which spots were formed for two years previously to the minimum of 1856, and, soon after this epoch, the apparent commencement of two fresh belts of spots in high latitudes, north and south, which have in subsequent years shown a tendency to coalesce, and ultimately to contract, as before, to extinction." Spörer fortunately took up the work where Carrington left off, and his observations extended over the period 1861—1879. These were published in four different volumes,† and the conclusions at which he arrived practically corroborated those of Carrington. In the last of these publications, Spörer summed up all the observations for the period 1854—1879, and published curves, showing the relation between the sunspot frequency for these years and the variation of the mean heliographic latitude of the spots.

The law of zones, as definitely formulated by Spörer, is as follows‡ :—"Un peu avant le minimum, il n'y a de taches que près de l'equateur solaire, entre $+5°$ et $-5°$. A partir du minimum, les taches, qui avaient depuis longtemps déserté les hautes latitudes, s'y montrent brusquement vers $\pm 30°$. Puis elles se multiplient, un peu partout, à peu près entre ces limites, jusqu'au maximum, mais leur latitude moyenne diminue constamment jusqu'à l'époque du nouveau minimum."

As solar prominences appear on any part of the disc, it was sufficient, in order to trace their distribution, to divide the sun's surface into nine zones of 10 degrees each. Since, however, spots seldom occur above latitude 40°, the width of the zones had to be considerably diminished. For the present inquiry, it was finally decided to group the spots into belts 3 degrees wide, for even zones of 5 degrees in width were found to mask many important characteristics.

The necessity for such narrow zones will be seen from the accompanying figure (fig. 1), in which the yearly distribution of spots is shown for the years 1879—1883, taking zones of 10 degrees, 5 degrees, and 3 degrees in width respectively.

* 'Observations of the Spots on the Sun,' made at Redhill by R. C. Carrington, F.R.S., 1863, p. 17.

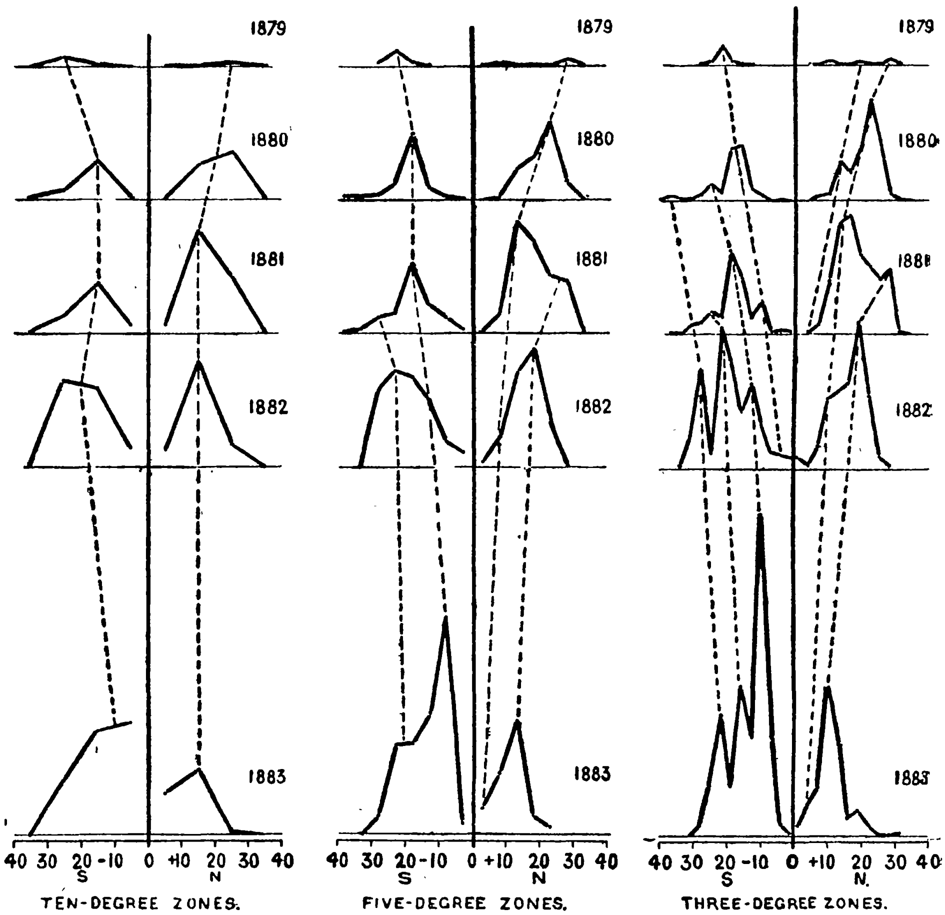
† 'Publication der Astronomischen Gesellschaft,' vol. 13 (Leipzig, 1874); 'Publication der Astronomischen Gesellschaft,' vol. 13. Fortsetzung (Leipzig, 1876); 'Publicationen des Astrophysikalischen Observatoriums zu Potsdam,' No. 1, vol. 1, Part I; No. 5, vol. 2, Part I.

‡ 'Comptes Rendus,' vol. 108, p. 486.

In these curves each broad vertical line corresponds to the solar equator, and the scales to the right and left of each represent the north and south latitudes respectively. The heights of the curves above each horizontal zero line indicates the different amounts of spotted area, and the scales of these are so arranged that the curves are all proportional to the spotted area.

The curves themselves are formed by determining the mean spotted

Fig. 1.



DISTRIBUTION OF SUN'S SPOTTED AREA.

FROM 1879–1883.

area for each zone, and plotting each value at the point representing the mean latitude of this zone; these points are then all joined together. Thus, in the case of the 0—10° zone, the mean spotted area is plotted at 5°, 10—20°, at 15°, etc. The other zone divisions are similarly treated, thus, 0—5° is plotted at 2·5°, 0—3° at 1·5°, etc.

In the 10° zone curves here shown there is only one maximum in each hemisphere for the years in question, and these, as indicated by the dotted curves which join them, do not progress gradually towards the equator, as would probably be the case according to Spörer's law. With 5° zones it is possible to detect the presence of two maxima in one or other of the hemispheres, all of which have a trend towards the equator in succeeding years. Still more detail is displayed in the 3° zones, and here is apparent a spot distribution and movement which is practically masked in the two preceding sets of curves.

The advisability of adopting 3° zones for the present investigation being thus apparent, the whole series of observations from the year 1861—1902 was treated in the above manner, the points plotted and the curves drawn as shown in the figure previously referred to.

This reduction was rendered comparatively easy by the fact that the Astronomer Royal has quite recently published* the values of the amount of sunspot area for each degree of latitude for each hemisphere from the year 1874—1902. For information previous to that date use was made of the detailed observations of the positions and areas of sunspots collected by Spörer in the publications already referred to, and curves for each year were drawn. For this period the curves employed were of a less degree of accuracy than those drawn from the Greenwich reduction, as the number of days of observation throughout a year was not so great.

Advantage was taken of the fact that Spörer's observations and those reduced at Greenwich overlapped during the four years 1874—1877, and a comparison of the curves from each series was rendered possible. The close similarity of these in each case showed that the reduction of Spörer's observations exhibited the chief features of the movements of centres of spot-activity as indicated by the Greenwich curves.

By thus employing Spörer's observations, curves for each of the 42 years from 1861—1902 inclusive were drawn in the manner described above, and these were placed vertically one under the other, like those shown in fig. 1 for the years 1879—1883.

In this way it was possible to trace the varying positions, as regards changes of latitude, of the centres of action, or maxima points of the curves, from year to year, just as was previously attempted in the case of the prominences. These centres of action were then connected by lines passing from one yearly curve to the next. It is worthy of remark that very little difficulty was met with in deciding the maxima points to be joined. There was always, throughout the whole period, a most distinct march of these points individually towards the equator, and the method of placing the curves one beneath the other rendered such movement at once obvious to the eye. There was only one instance where it seemed necessary that a march from lower to higher latitudes ought to be considered. This was in the southern hemisphere, in the years 1889 and 1890 (see Plate [2], Curve A). There

* 'Monthly Notices R. A. S.,' vol. 63, pp. 452—461.

was a small indication of the presence of a spot centre of action in latitude 19° in the former year, while next year the position of the centre of action was in latitude 24°. Since this case was unique, it was considered advisable not to connect these points together, but to leave the centre of action in the year 1889 as an isolated point.

The diagram (fig. 1) not only exhibits some of the types of curves met with, but shows how the various centres of maximum spot-activity were joined up with each other, year by year, for the period of time over which the curves extend, namely, from 1879, the year following a sunspot minimum, to about a sunspot maximum in 1883.

Considering the curves relating to the sun's northern hemisphere, it will be seen that in 1879, the year following a sunspot minimum, when the spots were ending a cycle near the equator, two new outbreaks occurred in latitudes about 20° and 30°.

These two centres of activity moved towards the equator next year, and by 1881 the former had disappeared, while the other rapidly grew in intensity and reached latitude 15°. During this year a new outbreak in latitude 30° made its appearance, and this in the two following years had an equatorial trend.

A somewhat similar occurrence took place in the southern hemisphere, each of the centres of action moving rapidly towards the equator.

It is interesting to note the rapid growth and decay of these centres of action, an example of which is shown commencing in 1879 in latitude 28° in the northern hemisphere.

Attention may particularly be drawn to the three prominent maxima of the curves for the southern hemisphere in the years 1882 and 1883, which indicate that at this period there were three definite centres of spot action in existence.

In order to bring within a small compass the results of the above analysis for the whole period of investigation (the above-mentioned forty-two curves, although drawn close together on a small scale, cover a strip of paper 5 feet in length), a method was adopted similar to that employed in the case of the prominence reduction.*

In the accompanying plates the two sets of curves marked A indicate for each hemisphere the changes in the positions of these centres of spot activity from year to year plotted at equal intervals of a year. The striped portion is deduced from Spörer's observations, and the remainder from the Greenwich reductions. These lines have been proportionally thickened to indicate approximately the relative amount of spotted area at these centres of action, or, in other words, the heights of the maxima points on the yearly curves. These curves thus indicate for each year the positions, as regards latitude, of the particular zones

* 'Roy Soc. Proc.,' vol. 71, pl. 6.

in which the centres of spot activity occur, and give an idea of the movements of these centres during each sunspot cycle.

In this paper these curves have been called "spot-activity tracks," but it is important to point out that this term is not necessarily applied to the proper motion of any individual spot, but simply to the changes of position of the regions in which they are most numerous. As, therefore, the term "spot-activity tracks" represents the different positions of the regions of greatest spot-activity, so "prominence-activity tracks" may be employed to indicate the equivalent variations as regards the prominences which were shown in a previous paper.*

These "spot-activity tracks" have possibly a terrestrial equivalent in the variations from year to year of the positions of the "Zugstrassen," or cyclone tracks of Köppen, it having been found that cyclones in general, which move in the direction of the great mass of air carried by primary currents, have a strong tendency to pursue somewhat the same tracks according to the place of origin.

For the sake of comparison, curves B, C, and D in each plate have been added. Curves B show the variations of the mean heliographic latitude of the total spotted area for each hemisphere as determined and described in a previous paper.†

Curves C illustrate the distribution and changes of position of the centres of prominence activity. These curves are somewhat different to those previously published,‡ being so arranged that they form a continuous series from the year 1870. The small circles in the years 1870—1871 represent Respighi's observations, the curves from 1872—1881 those of Tacchini, and the remainder, up to the year 1902, Ricco and Mascari's observations. The dotted curves previous to 1870 are intended only to give a rough idea of the prominence variations based on a repetition of the observations of 1872—1885.§ The last curves, namely, those marked D in the plates, represent the variation from year to year of the total spotted area on each hemisphere of the sun, and special attention was drawn in a previous publication‖ to the great differences between the two hemispheres at the times of sunspot maxima. The vertical broken and continuous lines indicate the epochs of sunspot minima and maxima as determined by combining the amount of spotted area on both hemispheres of the sun.

Reverting now to the curves marked A, which form the special subject of the present paper, the following *general* deductions may be made:—

1. From sunspot minimum to minimum there are three, but generally

* 'Roy. Soc. Proc.,' vol. 71, p. 446.
† 'Roy. Soc. Proc.,' vol. 71, p. 449.
‡ 'Roy. Soc. Proc.,' vol. 71, pl. 6 and 7.
§ 'Monthly Notices R. A. S.,' vol. 63, No. 8, p. 484.
‖ 'Roy. Soc. Proc.,' vol. 71, p. 246, footnote.

four, distinct "spot-activity tracks," or loci of movements of the centres of action of spot disturbance.

2. The first appearance of each of these "spot-activity tracks" occurs generally between a sunspot minimum and the following maximum. After about the epoch of maximum generally no new "spot-activity tracks" of large magnitude are commenced.

3. Their first appearance is mostly in higher latitudes than 20° in each hemisphere.

4. They are faintly indicated at first, become more prominent and distinct, and finally thin out and fade away.

5. They all fade away in regions close to the equator.

6. There seems to be a tendency for each successive "spot-activity track" to make its appearance in latitudes higher than the one preceding it.

7. At, or a little after, the time of sunspot maximum there is also a tendency for each "spot-activity track" to retain its latitude for a short time.

In the light of these curves it is interesting to analyse those formed by plotting the mean yearly heliographic latitude of spotted area for each hemisphere: these are given in the accompanying plates (Curves B). These latter curves represent the drift from year to year of the mean heliographic spot latitude, and illustrate Spörer's "Law of Zones." It will be noticed that each commences in high latitudes about the time of sunspot minimum, and gradually approaches the equator until the epoch of the following minimum, when a new cycle in high latitudes recommences.*

An important point to be noticed about this series of curves is that each is of a *wavy* nature. This peculiarity is clearly shown even in the plate illustrating Spörer's reduction† which covers the period 1854—1880. There the curves, representing the mean spotted area and the mean heliographic spot latitude for both hemispheres combined, were compared, and Spörer pointed out some anomalies between these mean curves and those formed by joining the actual points of observation. So conspicuous were these anomalies at one epoch (even after many of the peculiarities had been lost by combining the two hemispheres instead of treating them singly), that he drew attention to them in the following words‡: "Nun sieht man an den Beobachtungspuncten, welche bei der Breitencurve eingetragen sind, dass die aus specieller Rechnung hervorgehende Curve *ebenfalls eine*

* These curves should overlap, but the unit of time, namely, the year, here employed, masks this feature.

† 'Publicationen des Astrophysikalischen Observatoriums zu Potsdam,' vol. 2, Erstes Stück, No. 5, Tafel 32.

‡ 'Publicationen des Astrophysikalischen Observatoriums zu Potsdam,' vol. 2, Erstes Stück, No. 5, p. 81.

Welle liefern würde, und zwar hätte diese ihre grösste Erhebung gegen Ende des Jahres 1875." As will be seen from a further quotation from the same page, Spörer distinctly noticed subsidiary increases of spotted area and a reversion of spots to higher latitudes, and this drew from him the conclusion that the epoch of the following sunspot minimum would be late.

He wrote (page 81), "die Ursache, welche eine Erhebung der Breitencurve bewirkte, d. h. welche veranlasste, *dass in höheren Breiten als vorher Flecke entstanden*, dadurch auch Veranlassung gewesen ist, dass wiederum Vermehrung der Flecke eintrat und damit auch das Flecken-Minimum für längere Zeit verzögert wurde."

Again, from the solar observations made at the Kalócsa Observatory during the years 1880—1884, both years inclusive, Dr. Braun* depicted in a graphic manner the progressive changes in the mean heliographic latitude of the spots during this period, and drew attention to the differences between the mean curve and that passing strictly through the points of observation (fig. 2). The mean curve he found

Fig. 2.

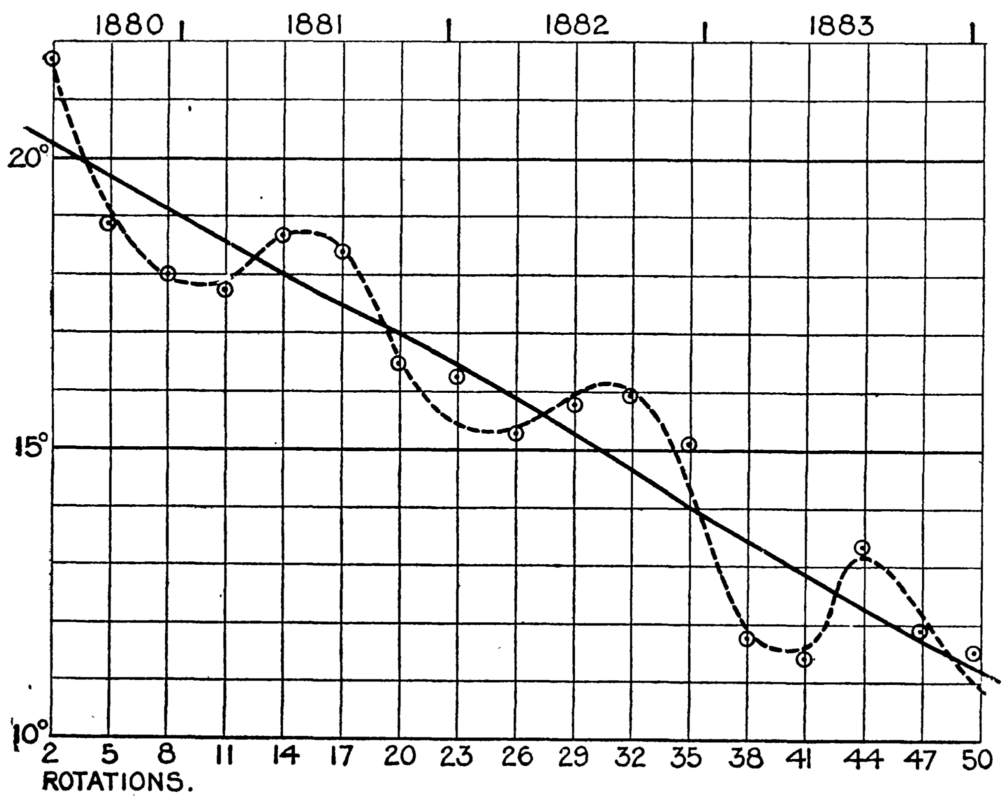


Diagram to illustrate for the years 1880—1883 the differences between the curve showing the decrease of the mean heliographic latitude for the entire spotted area of both hemispheres taken together (continuous curve), and that obtained by a less smoothed curve (dotted) passing through the points of the actual observations.

* 'Berichte von dem Erzbischöflich Haynaldschen Observatorium zu Kalócsa in Ungarn,' von Carl Braun, S.J. Münster i. W., 1886.

to continually approach the equator, but superposed upon the line of uniform descent was a series of minor oscillations. In this connection he wrote:* "Die Spörer'sche Entdeckung der in jeder Periode auftretenden Annäherung der Flecken-Zone gegen den Aequator findet somit in unsern Beobachtungen eine unmisskennbare Bestätigung. Allerdings sind die Zeichnungen nicht durchaus von demselben Gehilfen ausgeführt worden, und dieser Umstand mag einigen Einfluss in Bezug auf diese Wahrnehmung haben . . . Sehr auffallend erscheint eine gewisse secundäre periodische Schwankung der mittleren Breite mit einer Periode von etwa 1 Jahr und einer Amplitude von reichlich 2 Graden . . . Diese mag wohl einem Zufall zuzuschrieben sein, welche nur während dieser vier Jahre obwaltete, vielleicht auch mit dem Wechsel der Zeichner in Zusammenhang steht. Doch wäre es immerhin von Interesse, dass diese Wahrnehmung durch die Discussion anderweitiger Beobachtungen geprüft und eventuell näher untersucht würde."

The present investigation seems to throw light on these peculiar changes of curvature shown by the mean heliographic latitude curves. These latter (Plates [1] and [2], Curves B) are individually really nothing more than the *integration* of the corresponding Curves A. Every change of curvature in Curves B is due to either the outburst of spots in another "spot-activity track" or by one "spot-activity track" becoming more intensified in relation to another, or lastly by the extinction of a "spot-activity track" as the equator has been reached as shown in the Curves A.

To illustrate this, let the curve for the mean heliographic spot latitude in the southern hemisphere (Plate [2], Curves B) beginning in the year 1879 be considered. This is practically the period referred to above by Dr. Braun.

At this time there is only one "spot-activity track" (latitude 22°) in existence, as shown in Plate [2], Curve A; so Curve B consequently commences in the same latitude. By the next year the "spot-activity track" (Curves A) has reached latitude 17°, and a new one has made its appearance in latitude 25°. Curve B, therefore, takes the mean position of about 20°, when allowance has been made for the difference of intensity of these two tracks.

In the following year 1881 both these "spot-activity tracks" have approached nearer the equator, but another has appeared in latitude 25°, so that the mean latitude for the whole hemisphere has only slightly changed.

By the year 1882 still another "spot-activity track" has come into existence in latitude 28°, while the first "spot-activity track" mentioned

* *Ibid.*, p. 83.

What the actual connection between these two different systems of currents is, it is not possible yet to say, but these facts suggest a very close relationship.

In conclusion, I wish to express my thanks to Mr. T. F. Connolly, computer in the Solar Physics Observatory, for his assistance in making the reductions and drawing the numerous curves.

Conclusions.

The result of the investigation leads to the following conclusions:—

1. Spörer's law of spot zones is only approximately true, and gives only a very general idea of sunspot circulation.

2. Spörer's curves are the integrated result of two, three and sometimes four "spot-activity track" curves, each of the latter falling nearly continuously in latitude.

3. Spörer's, and many other previous reductions have indicated the peculiar "wavy" nature of the integrated curve, which peculiarity is here shown to be for the most part real and not due to errors of observation, etc.

4. Outbursts of spots in high latitudes are not restricted simply to the epochs at or about a sunspot minimum, but occur even up to the time of sunspot maximum.

5. The successive commencement of the "spot-activity tracks" in higher latitudes between a sunspot minimum and maximum seems to be closely related to the "prominence-activity tracks" at these periods.

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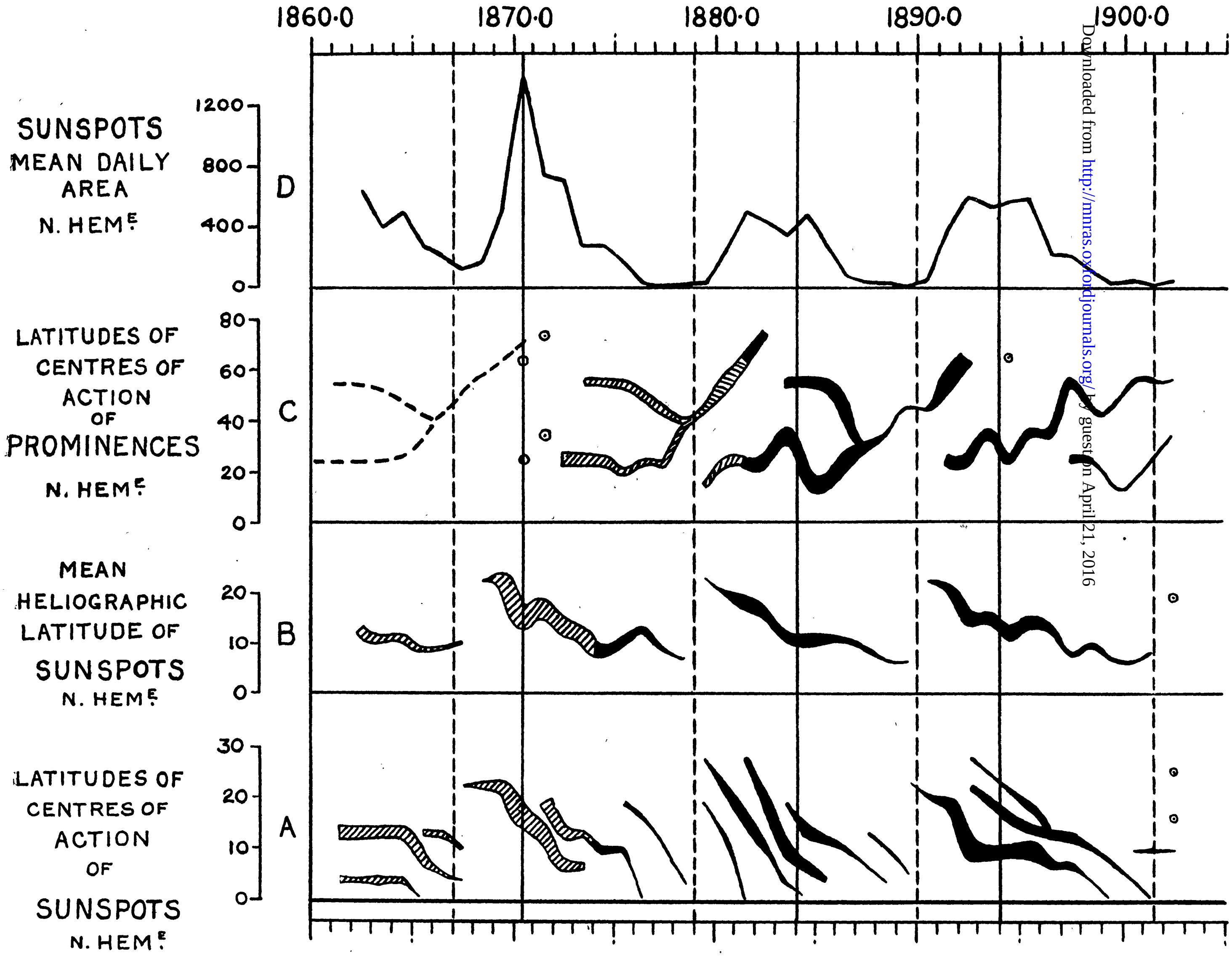
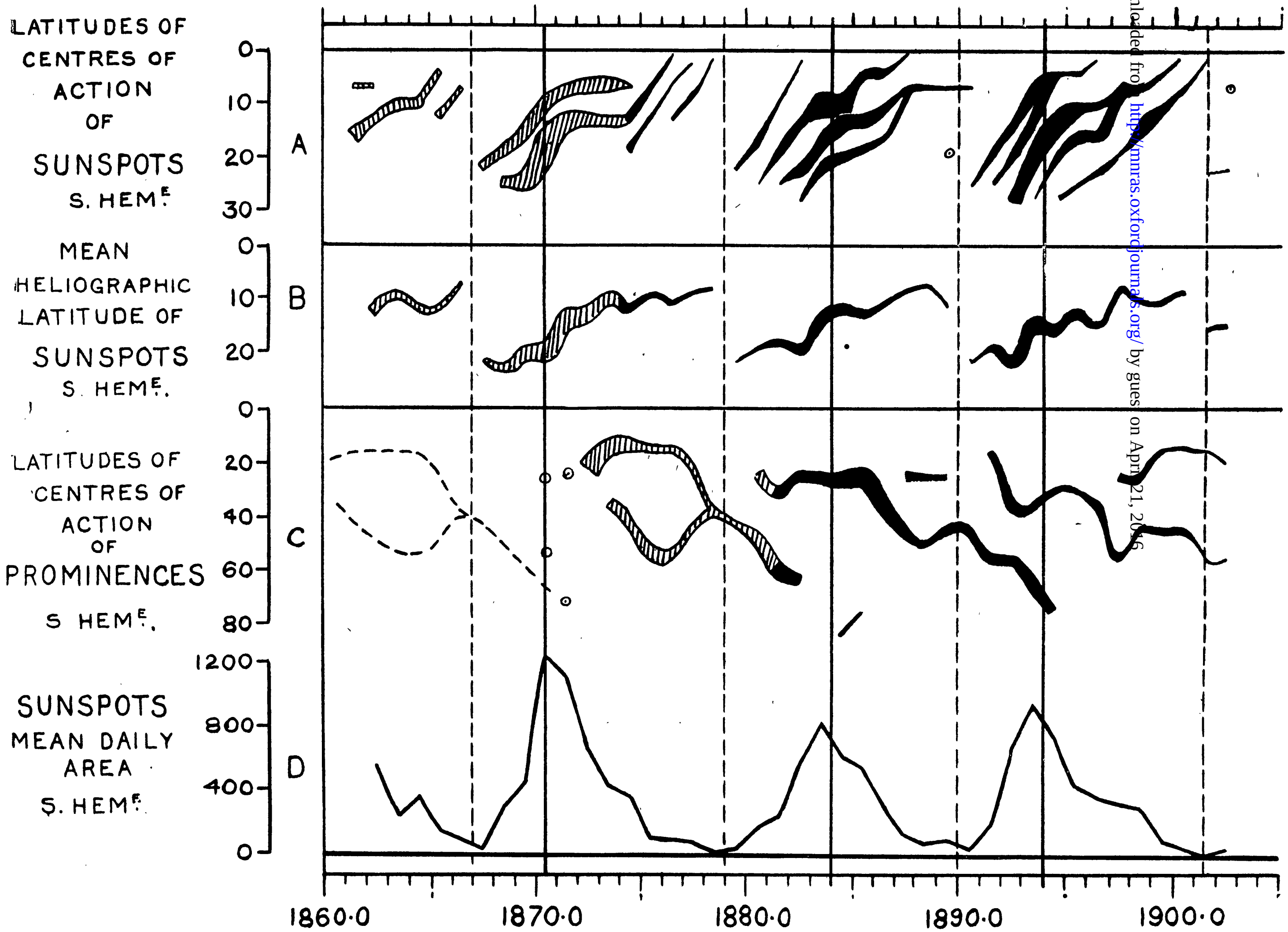


Curves showing the relation between the positions of the centres of action of Sunspots or "Spot-activity Tracks" (A), and Solar Prominences or "Prominence-activity Tracks" (C), the mean heliographic latitude of Sunspots north of the equator (B), and mean daily area of spots (D), for the northern hemisphere of the sun.

Note.—The continuous and broken vertical lines represent the epochs of sunspot maxima and minima as determined from the mean daily areas of the whole solar disc.



Similar curves to those on Plate [1], only in this case the southern hemisphere of the Sun is referred to. Vertical lines same as Plate [1].