Kodaikanal Observatory.

BULLETIN No. LXXXIX.

THE ROTATION OF HYDROGEN ABSORPTION MARKINGS AND THEIR HEIGHT ABOVE THE SURFACE OF THE SUN

Abstract.—The results in this paper are based on Kodaikanal Hα spectroheliograms during the years 1926—1929

The speed of rotation of hydrogen absorption markings has been determined by measurements near the central meridian for successive rotations of the same marking. Near the equator the sidereal rotation is 14° 55 per day, that is, nearly the same as for spots, but the polar retardation, although evident, is less than for spots (see fig 1 and table I). The polar retardation evidences itself by a progressive increase in the slope of an absorption marking to the central meridian at each successive rotation (see figs 2 and 3 of plate).

The heights of hydrogen absorption markings have been deduced from the time required for a marking to pass from the eastern limb of the sun to the central meridian or from the central meridian to the western limb. This time has been termed the quadrantal time of the marking. Since an absorption marking usually cuts the limb of the sun at quite definite latitudes, the quadrantal times at these latitudes can be determined with exactness. If the height of an absorption marking above the sun's surface were zero, its quadrantal time would be that required for a quarter rotation (synodic) of the sun, but the quadrantal times are actually found to be less than the latter as a result of the height of the absorption markings above the surface of the sun. For the edge of the absorption markings nearer the limb the average quadrantal time is 5·55 days, and for the edge farther from the limb 5·65 days, compared with 6·82 days for a quarter rotation (synodic) of markings. The deduced heights of the two edges are 33″·5 and 28″·0 respectively, the average height of the prominences (Ca) at the limb being 46″. Consequently it follows that the lowest parts of prominences do not show on the disc by absorption. The lowest parts of prominences are believed to show on the disc only by emission, being represented by the bright margins at the edges of absorption markings and the centre of bright margins appears to have a height of about 12″, deduced from the quadrantal time of 6·1 days. As the average heights of prominences at the limb includes the finest detail of prominences it is not surprising that these heights are greater than the heights found for the absorption markings.

The level of Hα spectroheliograms is found to be 6″·3, or 4,590 kms above the photosphere. This is the level of the chromosphere, and all the heights obtained in this paper are consequently to be understood as heights above the chromosphere.

The rotation of calcium absorption markings (filaments) has been studied by L d' Azambuja[1] who interpreted the apparent acceleration of rotation near the limb of the sun as an effect of the height of markings above the surface of the sun, and he estimated their heights accordingly. There can be little doubt that his interpretation is correct.

A study of this effect has now been made making use of the Kodaikanal spectroheliograms for the four years 1926—1929, taken with the Hα line. The method of measurement from which the heights of the absorption markings are deduced differs from that of d' Azambuja who measured the varying longitudes* of markings as they crossed the sun's disc. I find that longitudes near the limb of the sun cannot be measured accurately since a small error in a position near the limb leads to a considerable error in the deduced longitude. But it is here, near the sun's limb, where the apparent acceleration of rotation is greatest and where it is most desirable to know the longitudes and just here where the longitudes are subject to the largest errors. Moreover with such measures it is not simple to co-ordinate the results of different markings since they cannot be measured all at the same selected longitude, but have to be taken where they are found on photographs taken generally at daily intervals.

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[1] L. d' Azambuja, Comptes Rendus, 176, 950, 1923.

* Longitudes measured from the central meridian are invariably meant in this paper.

An examination of figs 4—8 of the plate accompanying this bulletin will show that hydrogen absorption markings at the limb cut the latter at quite definite latitudes It is a simple matter to measure these latitudes with sufficient accuracy The time when these latitudes reach the central meridian of the sun can be accurately deduced from photographs taken when the absorption marking is near the central meridian since the errors of longitude are then small The method used in this paper has consequently been to measure the time interval required for an absorption marking to travel from the east limb of the sun to the central meridian and from the central meridian to the west limb It is convenient to have a name for these time intervals and they will be referred to as quadrantal times since they are the times required to traverse a quadrant of the sun The quadrantal times for different markings in the same latitude zone can be immediately compared There are naturally some disadvantages in the method in that it does not give as many chances of measurement as are available on the disc near the limb but it possesses a very great advantage that the necessary measures can be made very rapidly and sufficient accuracy can be obtained with comparative ease The virtue of the method adopted in this paper lies in the fact that absorption markings are generally inclined to a meridian of the sun so that photographs taken at daily intervals will generally catch a marking cutting the limb at one place or another along the length of the marking; usually the absorption marking cuts the limb (or otherwise expressed the limb cuts the marking) in different places on two or more successive days The only difficulty is with the few markings which lie along a meridian of the sun such markings near the limb on one day will be completely past it on the next day, but the number of markings not caught in this way is small and their neglect will not appreciably affect the result

The quadrantal times so obtained will be an index of the heights of the absorption markings If the height above the sun s surface is zero the quadrantal time will be equal to the time required for a quarter rotation of the sun The greater the height of the marking the less will be the quadrantal time

The Level of Hα Spectroheliograms

We have hitherto spoken of the heights of absorption markings above the surface of the sun without specifying which surface exactly is meant In deriving the heights we have only used the central meridian of the sun which is the same for all levels and the limb of the sun in Hα light The level of the surface to be considered is therefore the level of the limb of the sun in Hα light The height of this above the photosphere can be measured by comparing the diameters of the sun in Hα light and in light from the adjacent continuous spectrum† The diameters found are 60 03 mm for Hα images and 59 64 mm for the continuous spectrum The deduced height is 6 3 or 4 590 kms above the photosphere that is probably identical with the top of the chromosphere which in calcium light has an average thickness of 5,000 kms Consequently the surface of the sun which has been considered in this paper is the upper surface of the chromosphere and the heights which are deduced for absorption markings etc are heights above the chromosphere

Mean Rotational Speed of Hα Absorption Markings

The true speed of rotation of absorption markings can be obtained from measurements near the central meridian where the height is so much foreshortened that its effect is inappreciable Day to day measures are subject to the irregular movements of markings and the effect of errors of measurement would be appreciable

It is curi us that n n has m nti n d (far a I am aware) that the l mb of th sun in Hα l ght may ha e a double edge yet it is l arly in K daik nal sp tr h l ogr ms good d y The us f th doubl dge f th sun disc is not instrumental in the n f being d t astigm tism o th ptical def ct f th p tr h l graph but is instrumental being probably du to th fact that th spectroh h graph mploys a fixed width f th se ond l t n the arrow line structure of th Hα lin at the limb The s paration of the tw dges in Kodaikan l H spectr h l grams is about varying somewhat in diff r nt pl ces

† D Azambuja has also used this m th d fo determining l l f sp t h l gr m but ot for Hα M udon Annales tome VIII fas II 1930

‡ St John Astr phys al J urnal 32 36 1910

§ Abetti howe er find th thi knes f th hydrog n hromoshper to be fr m 9″ t 10″ Ob rvat ry 49 89 1926

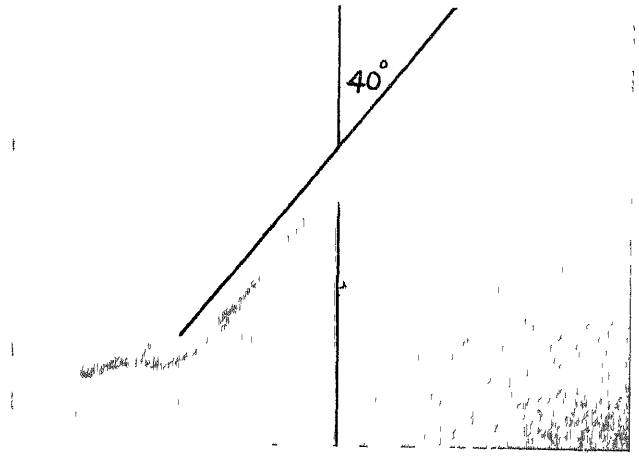

Fig 2 1927 Aug 2, $3^h\ 51^m$ G C T Compare with fig 3 below

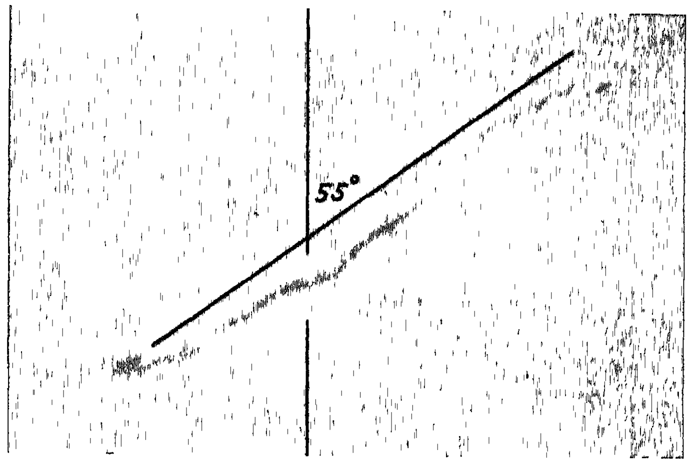

Fig 3 1927 Aug 29, $3^h\ 00^m$ G C T

This is the same dark marking as fig 2 after a complete rotation of the sun The slower speed of rotation in higher latitudes shows by the increased slope of the marking to the central meridian which is indicated by the vertical line

Fig 5 1927 Aug 23

This is the same marking as figs 2 & 3

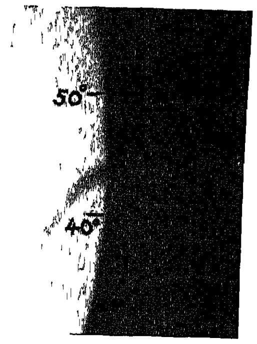

Fig 4 1927 Apr 8

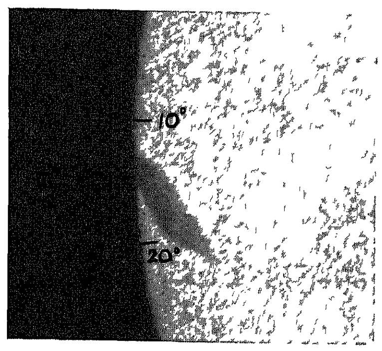

Fig 6 1928 Apr 2

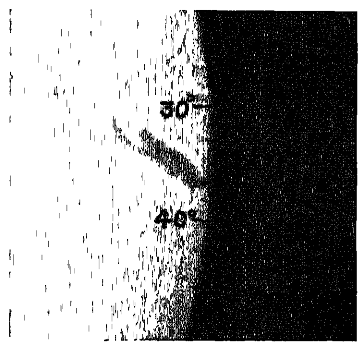

Fig 7 1928 Dec 30

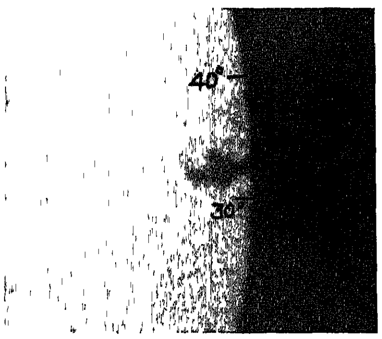

Fig 8 1929 Nov 30

Figs 4 to 8 are examples of dark markings which have been measured at the limb

This line represents the length of the solar diameter on the scale of the photographs

All the photographs are positives

It is best therefore to consider only absorption markings which have existed through a complete rotation of the sun and to find the times required for a complete rotation from the central meridian to central meridian All markings in the years 1926—1929 which have crossed the central meridian more than once were measured Measures were made on the western (or preceding) edge of the absorption markings for the sake of definiteness but no difference to the result would be caused by taking the centre or the eastern edge of markings From photographs showing an absorption marking near the central meridian the times of actually crossing the central meridian were deduced for intervals of 5° of latitude, assuming the approximate value of 13° per day for synodic rotation to reduce the positions near the central meridian to the actual time of crossing it Not many measures are possible in the belt between 0° and 5° owing to the paucity of markings of long duration, beyond latitude 40° most markings are parallel to the equator and the speed of rotation of such markings cannot be measured with accuracy The results do not vary greatly from marking to marking in the same latitudes, nor from year to year They are given below in table I

TABLE I —MEAN ROTATION OF Hα ABSORPTION MARKINGS

— — —										Means of all
Latitude	0°	5°	10°	15°	20°	25°	30°	35°	40°	21° 9
No of markings	3	11	19	37	47	40	30	23	6	
Days for complete synodic rotation	26 54	26 68	26 94	27 02	27 22	27 38	27 54	27 81	27 86	27 27
Degrees per day (synodic), ξ'	13 56	13 18	13 36	13 31	13·22	13 14	13 07	12 94	12 91	13 20
Degrees per day (siderial), ξ	14 55	14 47	14 35	14 30	14 21	14 13	14 06	13 93	13 90	14 19

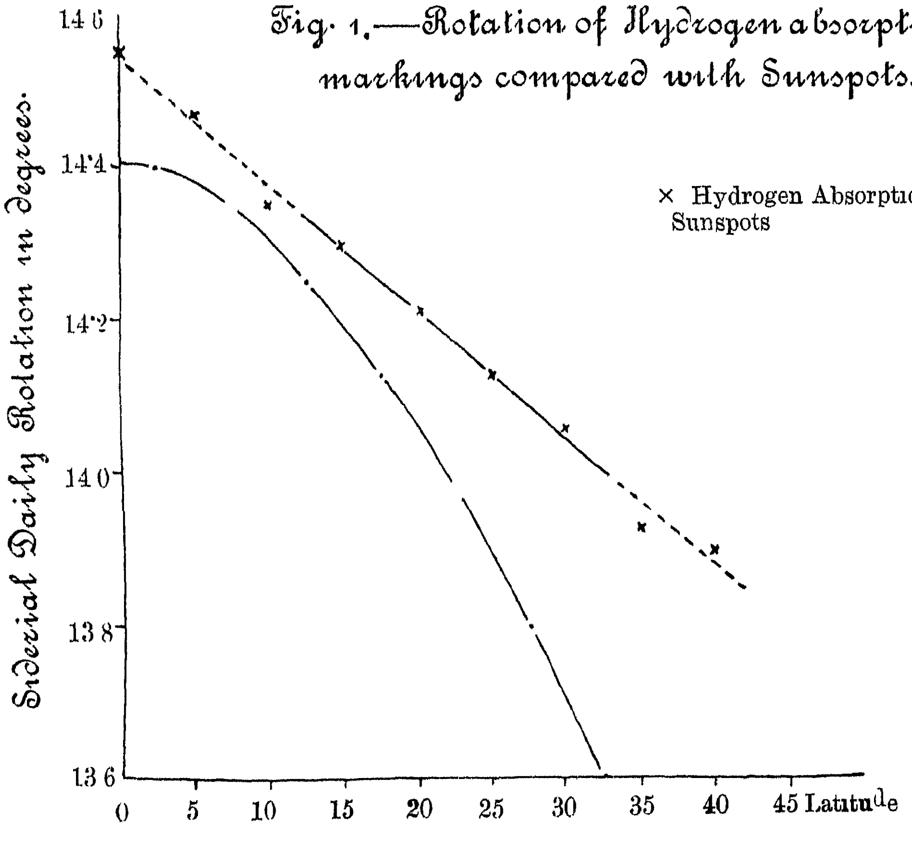

Fig. 1.—Rotation of Hydrogen absorption markings compared with Sunspots.

Fig 1 shows the curve of variation of siderial rotation with latitude compared with the rotation of sunspots, taking for the latter the unweighted means of Carrington, Spoerer and Maunder[1] It will be seen that although the rotation of absorption markings in low latitudes approximately agrees with that of sunspots, in higher latitudes their rotation is more rapid The retardation of rotation in higher latitudes is however clearly marked. This is well illustrated in figs 2 and 3 of the plate Fig 2 shows a long straight absorption marking stretching from latitude 7° N. to 35° N near the central meridian on 1927, August 2 at 3^h 51^m G M.T. The central meridian is indicated by a vertical line, and a line inclined to it at an angle of 40° is roughly parallel to the marking. If the higher latitudes are rotating more slowly than lower latitudes, they will gradually lag behind and increase the inclination of the marking to a meridian. This is neatly shown in fig. 3 in which is reproduced the same marking as fig 2 after one complete rotation of the sun, again near the central meridian on 1927, Aug 1929 , the line drawn at 55° to the central meridian indicates how much the inclination of the marking has increased since August 2 on account of the retardation of rotation in higher latitudes

The above noted increase in the inclination of absorption markings with increasing age lends support to the idea put forward in a previous bulletin[2] that the greater inclination in higher latitudes is caused by the retardation of rotation there

Heights of Hydrogen Absorption Markings

We are now ready to proceed with the determination and use of the quadrantal times of absorption markings, defined above as the time required for a point on a marking to pass from the east limb to the central meridian or from the central meridian to the west limb.

An example of the method of working may be given from figs 3 and 5 of the plate. The eastern edge of the filament in fig. 5 cuts the east limb at latitude 16° N at the time of the photograph, namely 3^h 26^m* G.M.T. on August 23rd. The same marking is shown near the central meridian in fig. 3 at 3^h 0^m G.M.T. on August 29th , measurement shows that latitude 16° N on the eastern edge of the marking was 3° W. of the central meridian at this time and therefore would have been actually on the central meridian 5 hours and 30 minutes before the photograph was taken. Consequently the time interval between the limb and the central meridian was from 23^d 3^h 26^m to 28^d 21^h 30^m, that is 5^d 18^h 4^m, or 5^d 75 for the quadrantal time at latitude 16° N

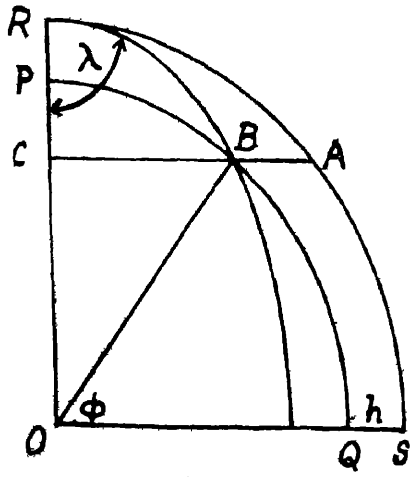

Fig. 9.

In fig. 9, PBQ represents the east limb of the sun from the pole P to the equator. OP is the central meridian of the sun and OQ the equator Let A be a point above the limb at height h above the surface of the sun, whose radius is a A rotates with a known speed until it reaches the limb of the sun at the point B, and has still to rotate through an angle which is denoted by γ before reaching the point C on the central meridian

The angle λ is measured by the quandrantal time in days multiplied by the angle through which A rotates (synodically) in 1 day. Denote the latitude of B by ϕ We require an equation connecting h and λ. Since h/a and $\cos^2\lambda$ are small compared with unity for the heights to be considered, the relation

[1] Hale, Astrophysical Journal, Nos 27, 213, 1908

[2] Royds, Kodaikanal Observatory Bulletin, No 63, 1920

* In the actual working all times were reduced to decimals of a day reckoning from a convenient zero hour Since most photographs are taken between 8^h and 9^h I.S.T , 8^h was made the zero hour as being more convenient than midnight.

between the height of the point A above the sun's surface and the quadrantal time can be expressed in the form

$$\frac{2h}{a} = \cos^2\lambda \ \cos^2\phi$$

The effect of the inclination of the sun's equator to the ecliptic is small and has been ignored

Since the majority of absorption markings are inclined to the meridian with the lower latitude end more westerly than the higher latitude end, [1] it follows that the eastern edge of such a marking cuts the limb (either east or west) at a lower latitude than the western edge The reverse is true for those exceptional markings whose inclination is in the opposite sense to the majority, and such cases were carefully distinguished It was soon found that the east quadrantal times are less for the eastern edge of an absorption marking than for the western edge, and the reverse is true for the west quadrantal times In the following table II, the east quadrantal times for the eastern edges and the west quadrantal times for the western edges have been grouped together under "edge nearer the limb" and similarly the east quadrantal times for the western edge and west quadrantal times for the eastern edge have been grouped under "edge farther from the limb" The daily synodic rotation ξ', has been interpolated from table I, and λ is obtained by multiplying this by the previous column The heights h were deduced by the formula of the previous paragraph

TABLE II —QUADRANTAL TIMES FOR Hα ABSORPTION MARKINGS AND THEIR CORRESPONDING HEIGHTS

Latitude	Number of markings	Edge nearer the limb				Edge farther from the limb			
		Quadrantal time in days (T_1)	ξ'	λ	Height h_1	Quadrantal times in days (T_2)	ξ'	λ	Height h_2
			°	°	″		°	°	″
0— 5	6	5 45	13 50	73 6	38 4	5 47	13 50	73 8	37 1
6—10	12	5 30	13 42	71 2	48 5	5 42	13 42	72 9	41 0
11—15	19	5 59	13 33	74 5	32 6	5 74	13 33	76 5	25 2
16—20	29	5 54	13 25	73 4	36 0	5 66	13 25	75 0	29 4
21—25	26	5 62	13 17	74 0	31 2	5 76	13 17	75 9	23 8
26—30	35	5 48	13 08	71 7	37 2	5 62	13 08	73 5	30 5
31—35	38	5 57	13 00	72 5	30 5	5 69	13 00	74 0	25 8
36—40	27	5 60	12 92	72 4	27 3	5 67	12 92	73 3	24 7
41—45	15	5 48	12 81	70 4	28 9	5 51	12 84	70 7	28 4
° 27 3*		Weighted means 5 555			″ 33 5	Weighted means 5 650			″ 28 0

As seen in the above table, the mean height of the highest portion of an absorption marking is 33″ 5 and the height of the lowest portion is 28″ 0 The average height of all prominences at the limb (in Ca K light since Hα photographs are not available) is 39″ 4, but it is to be remembered that all prominences are not represented in the markings chosen for measurement The mean height of the prominences corresponding to the markings measured is about 46″ Considering however that such heights include all the fine details seen in prominences it is not surprising that the fine details may not contain sufficient hydrogen to show by absorption when on the disc of the sun.

A surprising result is that the height of the lowest portions showing by absorption is 28″ 0, only 5″ 5 lower than the highest portions A greater difference had been anticipated, indeed a value approximating to zero for the height of the lowest portion had been expected, quite unjustifiably, as a brief examination of

[1] Kodaikanal Observatory Bulletin, No. 63

* Corresponding to the weighted mean of $\cos^2\phi$

spectroheliograms will show that the quadrantal times of the two edges of an absorption marking are only slightly different. This result is not to be supposed as possibly due to an erroneous value of the speed of rotation of absorption markings. No reasonable modification of the law of rotation can make the height of the edge of an absorption marking which is farther from the limb approach to zero. Hence there can be no doubt that a hydrogen absorption marking does not represent the whole of a prominence from base to summit, nor does it represent the lower portions only, but on the contrary only represents, in the average, a region of the prominence between 28″·0 and 33″·5 in height. Where then is the lower part of the prominence when the rotation has carried the prominence on to the face of the sun? An answer to this question is suggested in a later paragraph.

The above result that a hydrogen absorption marking represents such a narrow section of a prominence at the limb accounts for two observed facts. If the lowest part of an absorption marking were really at the zero level, we should expect the maximum height of the attendant prominence when this lower edge of the marking cuts the limb. As a matter of fact the greatest height of a prominence is nearly always one day earlier at the east limb and one day later at the west limb, than when the absorption marking cuts the limb. The second fact explained is the absence of any close relation between the shape of an absorption marking near the limb and the shape of the prominence at the limb. The reason is clear since the absorption marking proves to correspond to only a small section of the prominence.

It will be seen from table II that the quadrantal times do not vary appreciably with latitude but that the deduced heights are somewhat smaller in higher latitudes. The deduced heights depend on the two factors, $\cos^2\lambda$ and $\cos^2\phi$, the latter of which is chiefly responsible for the variation of heights with latitude. A modification of the law of rotation of absorption markings would however alter the variation of heights with latitude as the angle λ would be affected.

Table III shows that the quadrantal times diminish steadily from 1926 to 1929, i.e., the deduced heights are increasing. Whether this is a real effect or is in some way due to the selection of markings for measurement cannot now be said.

TABLE III.—VARIATION OF QUADRANTAL TIMES OF Hα ABSORPTION MARKINGS AND THEIR CORRESPONDING HEIGHTS IN SUCCESSIVE YEARS

Year.	Edge nearer the limb		Edge farther from the limb	
	Quadrantal time in days (T_1)	Height h_1	Quadrantal time in days (T_2)	Height h_2
		″		″
1926	5·627	30·0	5·738	24·7
1927	5·542	34·2	5·658	28·3
1928	5·499	36·2	5·580	31·9
1929	5·392	40·7	5·508	35·6

If, as the above reasoning has shown, a hydrogen absorption marking represents only an upper part of a prominence seen at the limb, it seems pertinent to enquire whether the lower parts of a prominence at the limb are seen at all when on the face of the sun. The only feature attached to a hydrogen absorption marking besides the marking itself is the bright margin on each side of the dark absorption. It has been pointed out[1] that practically every hydrogen dark marking is accompanied by bright margins on each side. It was shown that as the dark marking approaches the sun's limb, the bright margin on the side farther from

[1] Kodaikanal Observatory Bulletin, No 63

the limb becomes relatively brighter, whilst the bright margin on the limb side disappears through being hidden from view by the higher dark marking The method adopted at that time to give the height of the dark absorption above the bright margin could not be expected to give more than the order of magnitude of this height, and the difference of height found was 10″ It is now found possible to determine the height of the bright margin somewhat more precisely from their quadrantal times, exactly as has been done for the dark absorption Notwithstanding the fact that most dark markings are accompanied by bright margins, yet not often do the margins make a clear cut on the limb of the sun Not many can therefore be measured and the measures are not so definite as for absorption markings An example is shown in fig 5 of the plate, it is hoped that the reproduction will show the bright margin on the side farther from the limb, cutting the latter farther north than the absorption marking In the four years 1926—1929, only 20 bright margins were considered suitable for measurement without ambiguity Measurements were made on the middle of the place where the bright margin touches the limb of the sun and the results are given below in table IV

TABLE IV —QUADRANTAL TIMES AND CORRESPONDING HEIGHTS OF THE BRIGHT MARGINS OF Hα ABSORPTION MARKINGS

Mean latitude	Number	Quadrantal times in days (T_3)	λ	Height h_3
° 21 4	20	6 09 days	° 80 4	″ 11 6

The mean height deduced is 11″ 6, or about 16″ below the absorption marking which may be compared with 10′ for the order of magnitude deduced in the previous bulletin referred to above Considering the fact that it is only practicable to measure the middle point of the width of the bright margins and this has a height of 11″ 6, it seems reasonable to suppose that the lowest portions of the bright margin must be almost, if not quite, on the surface of the chromosphere

The above deduced heights for the different parts of an absorption marking do not give a complete explanation of the relation between an absorption marking on the disc and the prominence seen at the limb, but they do throw some light on it We have prominences at the limb extending to an average height of, say, 46″ The highest part of the corresponding absorption marking is 33″ 5 above the chromosphere and the lowest 28″ 0. The light used in obtaining the spectroheliograms is the centre of the Hα line whose fluctuations of intensity give us the well-known features of Hα spectroheliograms These fluctuations may be due to (1) fluctuations in the photospheric light seen through a partially transparent layer of hydrogen, (2) fluctuations in the number of absorbing atoms in the partially transparent layer of hydrogen, or (3) fluctuations in the emission and absorption of layers of hydrogen completely opaque to the photosphere below Since the prominences on the disc have no counterpart in the continuous spectrum we can exclude (1) above. Also, if (2) were effective, the bright margins of absorption markings would have to be interpreted as due to less absorption of photospheric light due to the removal of absorbing atoms either bodily or by excitation It is unreasonable to suppose that the presence of a prominence can lead to a diminution of the number of atoms capable of absorbing the Hα line. We are therefore driven to (3), namely that the brightening of the Hα line in a bright margin is due to brighter emission of the hydrogen itself and that the absorption marking is due to the absorption of light from this background by the cooler layer of hydrogen. The lowest parts of prominence then correspond to the bright emission seen at the margins of absorption markings but probably also underlying the whole absorption marking They are radiating more strongly than the general surface of the sun (in Hα light) but are not much raised above the surface of the chromosphere Since the total width of the bright margins (assumed to underlie the absorption marking) is greater than that of the absorption marking it follows on the above interpretation that the lower parts of the prominence are more extensive than the upper parts which is reasonable Absorption of this bright background can only be exerted by those higher portions of the prominence which are cool This absorption begins at a height of 28 0 (on the average) and extends to a height of 33 5 The parts of a prominence above this height are supposed not to contain sufficient absorbing atoms to effect appreciable absorption and are therefore not represented in the absorption marking It must be stated nevertheless that the edges of an absorption marking are generally quite sharp and unless we can see a reason why absorption should suddenly begin at a definite height so as to cause a sharp edge we must seek the cause in the build or structure of prominences

It must not be supposed without further examination that results obtained in this bulletin for hydrogen absorption markings apply equally to calcium absorption markings The two kinds of absorption markings may have somewhat different structures In the first place I believe I am correct in saying that K_3 absorption markings are not accompanied by bright margins similar to those in the case of hydrogen It is also possible if not probable that the heights deduced from measures of K_3 absorption markings would not be identical with those of $H\alpha$ absorption markings Further Evershed has shown [1] that in calcium prominences the gases at a height of 29 are moving westwards at about 1 km/sec faster than the prominences themselves ; if this movement is shared by hydrogen then in an absorption marking such as that illustrated in fig 3 the hydrogen must have passed completely out of the marking in less than 2 hours The absorption marking illustrated in fig 3 has a fairly typical width in round figures 6 000 kms and if the hydrogen in it is moving westwards at 1 km/sec it will have passed out of the marking in 6 000 secs or less than 2 hours as stated above Since absorption markings frequently last for months we would have to assume in such a case that the absorbing hydrogen must be continuously renewed from below

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[1] J E rshed M nthly N ti R A S 88 126 1927

KODAIKANAL,
22nd December 1930

T ROYDS
Director Kodaikanal and Madras Observatories

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