Kodaikanal Observatory.

BULLETIN No. XCV.

PROMINENCES AND RADIATION PRESSURE

BY

T. ROYDS, D.Sc.

Abstract.—Daily spectroheliograms of calcium and hydrogen prominences are available at Kodaikanal from the end of 1928. Comparison shows that quiescent prominences are of essentially the same form and height in both calcium and hydrogen, as has been concluded by other observers. This is also true of eruptive prominences in which hydrogen partakes of the upward motion evidenced in calcium. Since radiation pressure is only considerable in the case of Ca^+ atoms, this evidence is opposed to the theory of radiation pressure as the force supporting prominences and driving eruptive prominences away from the sun.

There appear to be differences in the relative brightness of the K line and the $H\alpha$ line in different prominences, and frequently in different parts of the same prominence. Owing to the effect of Doppler displacements, it is not possible for spectroheliograms to give conclusive evidence as to whether these variations in brightness are really due to varying proportions of the numbers of Ca^+ and H atoms.

It is pointed out that estimates of the amount of radiation pressure on Ca^+ atoms should take account of the radiation in the reversals of the Ca^+ lines. These estimates must await photometric measures in the Ca^+ lines.

Introduction.—The only theory which can in any satisfactory way explain the existence of the chromosphere and of the prominences is that of Milne * who showed that selective radiation pressure may be large enough to support atoms which have their resonance line in a part of the spectrum where the sun is radiating strongly. In this way he has successfully explained the formation of a chromosphere of ionised calcium, of prominences of ionised calcium, and has also given an explanation of the enormous velocities occasionally attained in eruptive prominences, a problem which, till then, had baffled solution. Notwithstanding these notable successes of Milne's theory, it does not suffice to give a complete explanation of the observations made on the sun's chromosphere and its prominences. It is observed that Ca^+, H and He are always present in the chromosphere, reaching almost to the same heights, and that prominences invariably exhibit the lines of these three elements. It is extremely improbable that the radiation pressures exerted by sunlight on the atoms o Ca^+, H and He and the masses of these atoms are also so nicely adjusted that the atoms of these three elements are delicately balanced together at the same heights above the sun's surface. Indeed Gurney† has already pointed out that the radiation pressure on hydrogen is 10^6 times smaller than on ionised calcium, and on helium 10^{13} times smaller. Electrical forces may be ruled out as they would not operate on neutral hydrogen and helium. Turbulence has also been invoked‡, but there are serious objections to the magnitude of the velocities which have to be postulated.

Recent Observations.—The question of the forms and brightness of prominences in different spectrum lines has occupied the attention of solar observers from almost the beginning of the observation of prominences, but the question has attracted more attention recently with a view to elucidating the nature of the

---

* Milne, M.N., R.A.S., 84, 354—1924; 85, 111—1924; 86, 8—1925; 86, 578—1926 and 87, 459—1926.

† Gurney, M.N., R.A.S., 88, 377—1928.

‡ McCrea, M.N., R.A.S., 89, 483 and 718—1929.

forces at play. Perepelkin[*] finds that the ratio of intensities $H\alpha : D_3$ decreases with height in prominences. Minnaert and Slob's measures[†] do not agree with Perepelkin's, and the former interpret the varying ratio by varying self-absorption of $H\alpha$. They have also measured the intensity ratios of H : K and of $H\gamma : H\delta : H\epsilon$. Slob[‡] has continued observations of the ratio of H : K and finds a value decreasing with height, instead of Minnaert and Slob's constant ratio.

Pettit[§] has compared spectrohelioscopic observations of prominences in $H\alpha$ with spectroheliograms in calcium K line, observing mainly quiescent prominences and those active ones which were drawn to an area of attraction on the sun's surface. He finds that prominences generally show the same form in $H\alpha$ as in K, even to considerable detail, except that moving streamers and knots in the active prominences are either absent in $H\alpha$ or only represented by thin lines where there are broad ribbons in K. He interprets these differences as evidence that the attractive force is electrical in origin and he also finds evidence of repulsive electrical forces.

Perepelkin[||] has also discussed the radial velocities of prominences, their form and intensities in different spectral lines. He finds that radial velocities decrease in the order Ca^+, H, He; in most cases prominences have the same form in Ca^+, H and He but in other cases the extents vary in the following decreasing order Ca^+, H, He, metallic lines; also that the ratio of intensities of the lines $H\epsilon : H$ is very variable, in the average 0·37, and decreasing with increasing radial velocity. He concludes that radiation pressure must play an important role in the production of prominences although quiescent prominences cannot be caused by radiation pressure.

Kodaikanal Spectroheliograms.—New material for the study of the forms and heights of prominences in calcium and hydrogen has been obtained at the Kodaikanal Observatory from the end of 1928. Owing to the increase in the sensitiveness of panchromatic plates about that time, it became practicable to photograph the $H\alpha$ prominences by means of the Kodaikanal $H\alpha$ spectroheliograph with reasonable exposure times. Since January 1st, 1929, the daily observing programme has been extended to include one $H\alpha$ prominence photograph. The solar diameter on both $H\alpha$ and K images is about 60 mm. The material studied for this bulletin comprises the $H\alpha$ and K spectroheliograms of the limb of the sun from the beginning of October 1928 to the end of 1931. Whenever possible, on each day a K prominence plate is taken first, then an $H\alpha$ photograph and finally another K photograph. In this way it is possible, by comparing the two K photographs, to be certain what changes have taken place in the prominence before drawing conclusions as to the differences of form and height in $H\alpha$ as compared with K. Of course, simultaneous photographs would be still better but this is not possible with the instrumental equipment at Kodaikanal. Yet it is considered that the study of alternate photographs is infinitely better than a comparison of a drawing in $H\alpha$ with a K photograph. The interval between successive photographs is often not more than 10 minutes, and in the majority of cases the changes in prominence form in this interval are trifling. The time occupied in taking the photographs does not permit of this interval being shortened appreciably.

Properties of Photographic Plates.—Before drawing definite conclusions regarding the differences in apparent brightness of different parts of prominences in Ca^+ and $H\alpha$ photographs, it has to be remembered that these photographs are not taken on the same kind of plates. For Ca^+ prominences, rapid plates of the ordinary type are used, whereas for $H\alpha$ prominences rapid panchromatic plates are employed. These two kinds of plates do not have the same characteristic properties. A study of their characteristics has been made with light of the same wavelength to which they are exposed in the spectroheliographs, the photometric measures being made with a Hartmann photometer. The photometric plates were treated and developed in a manner as similar as possible to the spectroheliograms. It is found that the gamma values of the panchromatic plate exposed to $H\alpha$ light is nearly three times that of the ordinary rapid plate exposed to K light. This has an important bearing on the interpretation of the fainter parts of a prominence. On

---

[*] Perepelkin, Z.f. Physik 49, 295.

[†] Minnaert and Slob, B.A.N. No. 187, 176—1930.

[‡] Slob, B.A.N. No. 218, 120—1931.

[§] Pettit, Publ. A.S. Pacific 63, 207—1931.

[||] Perepelkin, Z.f. Astrophysik, 3, 338—1931.


Fig. 7. Ca.


Fig. 8. Ca.


Fig. 8. H*a*.


Fig. 7. H*a*.


Fig. 9. Ca.

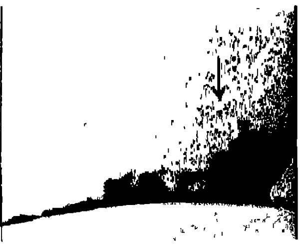
Fig. 9. H*a*.

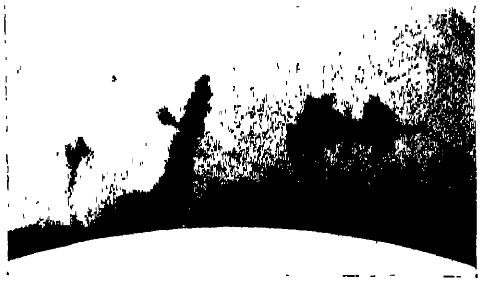
Fig. 10. Ca.

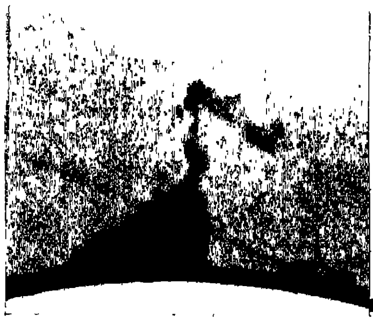
Fig. 11. Ca.

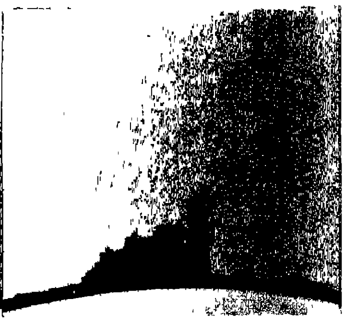
Fig. 11. H*a*.


Fig. 10 H*a*.


Fig. 12. Ca.


Fig. 12 H*a*.


Fig. 13. Ca.


Fig. 13. H*a*.

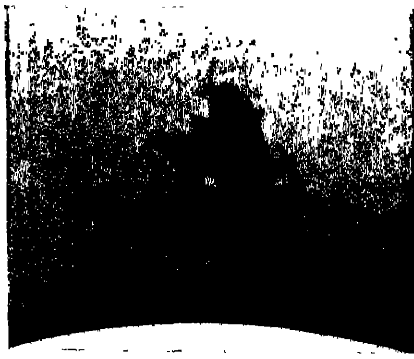
Fig. 14. Ca.

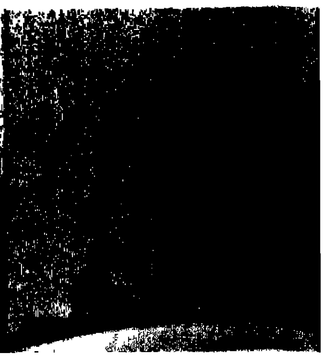
Fig. 14. H*a*.

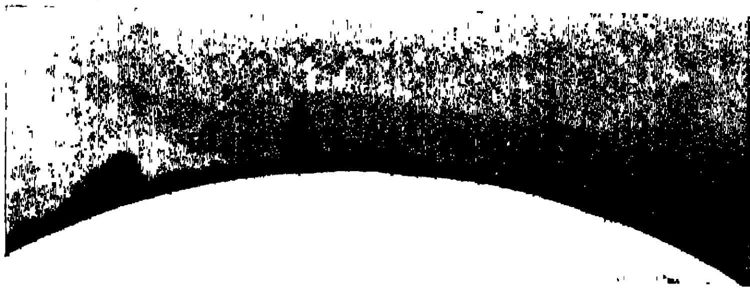
Fig. 15. Ca.

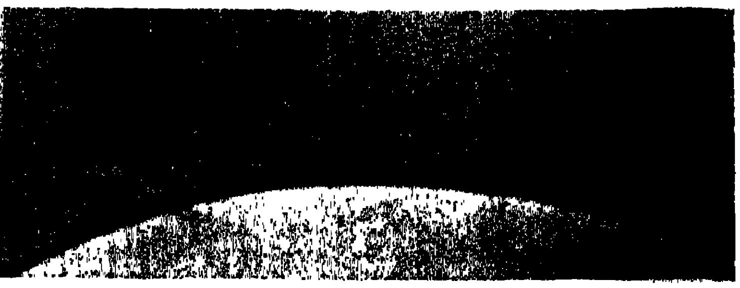
Fig. 15. H*a*.

47

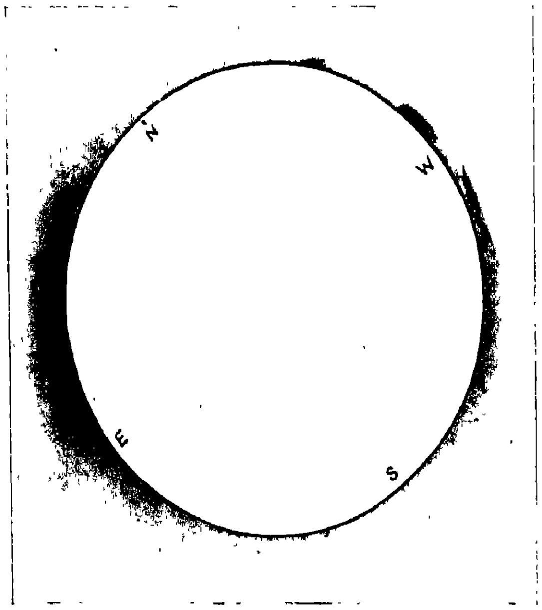

Fig. 1. Ca.

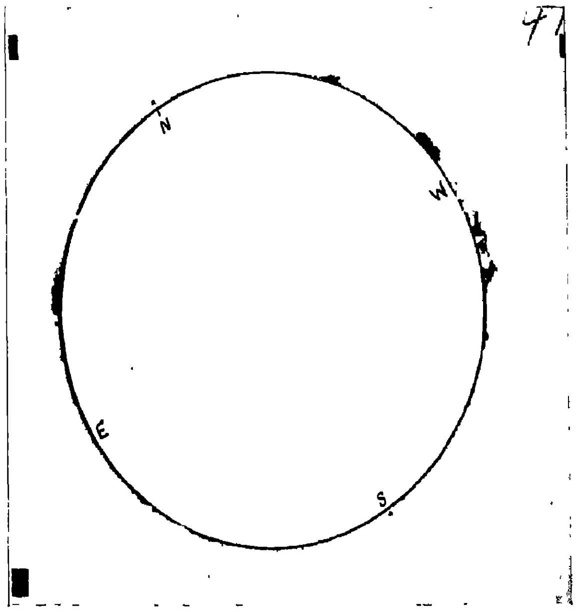

Fig. 1. Hα.

Fig. 2. Ca.

Fig. 2. Hα.

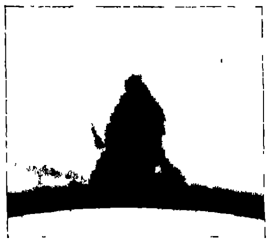

Fig. 3. Ca.

Fig. 3. Hα.

Fig. 4. Ca.

Fig. 4. Hα.

Fig. 5. Ca.

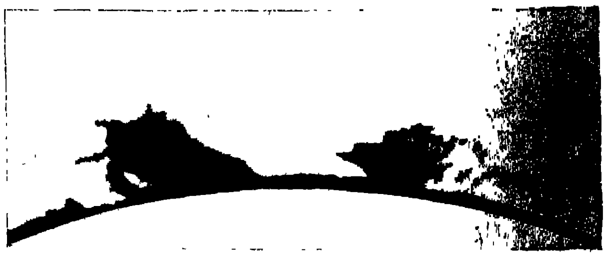

Fig. 5. Hα.

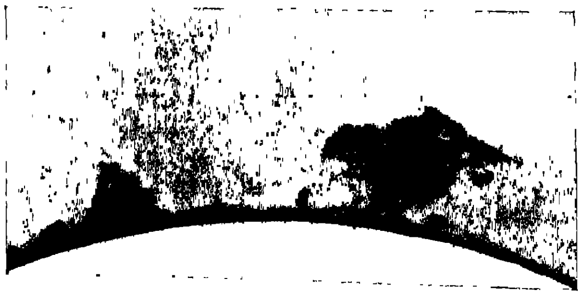

Fig. 6. Ca.

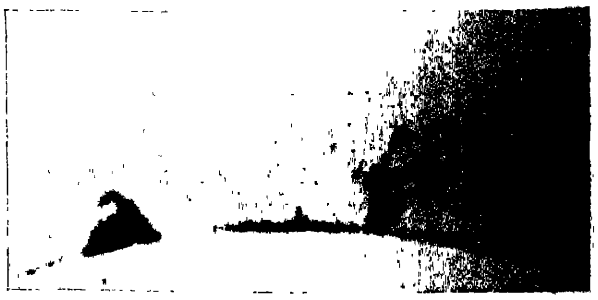

Fig. 6. Hα.

account of the higher gamma value the contrast between the fainter and brighter parts of a prominence in an $H\alpha$ photograph will be greater than in a Ca+photograph. Assuming equal effective exposure in the brightest parts of prominences, it follows that faint details will be lost in $H\alpha$ photographs much sooner than in Ca photographs. Consequently we see that at least part of the explanation of the absence from $H\alpha$ photographs of the faintest parts of prominences lies in the different photographic properties of the plates used. Nevertheless, not all the differences between $H\alpha$ and Ca prominences are due to this, as may be seen especially clearly in figures 7, 8, 9 and 11 where the relative brightness in different parts of the Ca prominences shows that the absence from the $H\alpha$ prominence is not a mere contrast effect.

Effect of Sky Conditions.—It should also be remembered that sky conditions at the time of observation also affect the visibility of the fainter details of prominences. For instrumental reasons the effect of poor skies in extinguishing faint detail is greater in the case of the Kodaikanal K spectroheliograms than for $H\alpha$ spectroheliograms, i.e., the effect is in the opposite direction to that of the characteristic properties of the photographic plates as mentioned in the previous paragraph. In all of the photographs reproduced in plates I and II accompanying this bulletin the sky conditions were at least fairly good so that any effect of this kind may be left out of consideration in comparing these photographs.

Effect of Doppler Displacements on Spectroheliograms.—As is well known, the spectroheliograph, from its nature, cannot give a true picture in the presence of Doppler displacements. This defect is serious in the study undertaken in this bulletin, namely of the true form of prominences. If a part of the prominence is moving in the line of sight to the extent of displacing the line off the second slit of the spectroheliograph, this part of the prominence will be missing in the photograph. Although both the Ca and $H\alpha$ spectroheliograms will be subject to this effect in a similar way, it is not practicable to arrange that the effect will be of exactly the same amount in the two spectroheliographs. The width of the second slit of the Kodaikanal $H\alpha$ spectroheliograph is 2 × 0·15 A, corresponding to a Doppler displacement due to 7 km/sec in either direction whereas in the K instrument the width of the second slit is 2 × 0·25 A, corresponding to 20 km/sec in either direction. Although Doppler shifts of these amounts will not suffice to displace the lines completely off the slit on account of the widths of the lines themselves, yet it is clear that Doppler displacements will have a greater effect on the $H\alpha$ spectroheliograms than on the Ca spectroheliograms.

The only way of eliminating the effects of Doppler displacements in prominence photographs is by photographing prominences during a total eclipse with an objective prism. This has been done on many occasions and all the available evidence seems to be that the form and height of prominences is the same in at least the elements Ca^+, H and He. On account of the infrequency of eclipses, the amount of evidence obtained in this way is not great.

Plates I and II.—A few of the prominences photographed in Ca^+ and $H\alpha$ have been chosen for illustration in Plates I and II accompanying this bulletin. An adequate representation of all the types of prominences photographed in three years would require a large number of plates but the examples chosen for reproduction have been selected in order to show not only typical prominences but also some of the extreme cases. Plate I shows chiefly prominences where the resemblance between the Ca and the $H\alpha$ forms is very close. Figure I shows the whole limb of the sun on the 27th February 1929, with the calcium photograph almost indistinguishable from the hydrogen photograph. In Fig. 1 the photographs are reproduced on the same scale as the original. The remaining figures are enlarged 3·9 times. Figs. 2 to 6 illustrate prominences all of the quiescent type, except the one on the right of Fig. 6. With this exception, these prominences are all of the solid massive type, especially in $H\alpha$, and it is seen that the outlines and heights are practically identical in Ca and in $H\alpha$. Figs. 2 and 4, especially, indicate that the $H\alpha$ photographs, are not suffering from underexposure relative to the calcium photographs, for in these the $H\alpha$ prominences are relatively more dense and compact. Types of prominences which occur more frequently than the number chosen for illustration would indicate are shown in figures 7 and 8. Here massive prominences in Ca light show only in skeleton form in $H\alpha$, although there is nothing to suggest underexposure in the latter. Whilst generally it is the strongest parts of the Ca prominence which form the skeleton structure in $H\alpha$, this is not invariably the case. It would appear that in prominences of this type the ratio of the number of Ca : H atoms is not the same in all portions of the prominence, but conclusive evidence is not available in consequence of the possibility of Doppler displacements, although no radial motion was noted in visual observations in Hα. The differences between Ca prominence and its Hα skeleton would appear to be due to differences of brightness rather than to any essential difference in the forms of the prominence in the two elements. Essential differences in the form of a prominence in Ca and Hα have only been noted in prominences of the type illustrated in Fig. 9, where the arm indicated by the arrow in the Ca prominence, although one of the strongest parts of the prominence, is entirely missing in Hα. Its absence is not due to changing form as it is also present in the Ca photograph taken before the Hα. Presumably this is the type observed by Pettit[*], but in Kodaikanal experience clear cases of such phenomena are comparatively rare. Fig. 10 illustrates a prominence, eruptive in parts, in which portions are relatively faint in Hα. Generally in eruptive prominences, the Hα counterpart is relatively fainter than in the cases of massive quiescent prominences and the degree of faintness varies considerably in different cases. Compare Figs. 6, 10, 12, 13 and 14 in this respect. Probably Doppler shifts due to radial motion are responsible for some, at least, of these effects. In Fig. 11 the high streamer is missing in Hα although not so extremely faint in Ca compared to portions which are reproduced in Hα. Figs. 12, 13 and 14 illustrate types of eruptive prominences. Fig. 12 is the jet or fountain type over a sunspot and changes are taking place rapidly in its form. There is, however, nothing to indicate essential differences of form and height in the Hα photographs. In Figs. 13 and 14 the changes are slower and apart from differences of brightness there appears no essential difference in the forms and heights of the Ca and Hα photographs. It would have been easy to multiply examples of eruptive prominences. In cases where rapid motions of ascent are taking place it is easily verified that the Hα form is ascending with the calcium. Even in the case of the remarkable prominence of 1928 November 19[†] the form is, up to the limits of the plate at $8'$ above the sun's surface, identical in Hα light (in the only Hα photograph taken) with the Ca counterpart. Indeed if the H atoms did not partake completely of the same motion as the Ca atoms, there could not be the similarity of form and height as is evidenced in eruptive prominences. For even if the forms were similar in the beginning, a difference in the speed of ascent would soon cause them to cease to bear any resemblance to each other at the same heights above the sun's surface. The mere fact that ascending prominences have essentially the same form and height in Ca and in H would suffice to indicate that the motions of Ca and H must be identical. The essential identity of eruptive prominences in their form, height and motion in Ca and H has a most important bearing on the radiation pressure theory. Perepelkin [‡] finds, on the other hand, that the Doppler displacements of Ca^+ and $H\epsilon$ are not equal, the ratio of radial velocities for $Ca^+ : H\epsilon$ being greater than unity, but these relate to movements in the line of sight which may not be caused in the same way as movements of ascent or descent in the sun.

Fig. 15 is an extreme case of the difference of brightness of Hα in different prominences. The middle prominence is very much fainter in Hα than its brightness in Ca^+ would warrant. As a Doppler displacement amounting to 1·5 A was observed visually in the middle prominence, it is probable that the faintness in Hα is due to this cause.

Selective Radiation Pressure on Ionised Calcium.—Notwithstanding the fact that radiation pressure cannot support the atoms of H and He in the sun's chromosphere, yet it cannot be denied that selective radiation pressure must operate at least on the atoms of Ca^+ in accordance with Milne's theory. Milne has shown [§] that the amount of pressure of radiation from the sun's photosphere is of the order required to support a Ca^+ chromosphere, any local enhancement of photospheric brightness driving out the Ca^+ atoms to form a prominence. The calculated amount of the radiation pressure has been modified from Milne's original estimate, chiefly by taking more accurate account of the exact amount of energy absorbed in the Ca^+ lines.[‖] It has to be pointed out that the energy absorbed by Ca^+ is still incorrectly estimated because the background

---

[*] Pettit, loc. cit.

[†] Royds, M.N., R.A.S., 89, 255—1928.

[‡] Perepelkin, loc. cit.

[§] Milne, loc. cit.

[‖] Minnaert, Z. f. Physik, 45, 610—1927. Unsöld, Ap. J. 69, 209—1929. See Menzel, M.N., R.A.S, 91, 628—1931.

of radiation from which the Ca^+ chromosphere is absorbing light is not the continuous spectrum from the photosphere, nor even the continuous spectrum after passing through the layer absorbing the wings of the Ca^+ lines. Taking the K line, it is well known that Ca^+ atoms above the photosphere are so conditioned as to give rise to the portions of the line known as K_1, K_2 and K_3. The K_1 absorption in the wings of the line comes from the deepest layers, the K_2 reversal is caused by conditions in a higher layer not yet satisfactorily explained and the K_3 absorption in the centre of the line is caused by the highest layers. If the sun's chromosphere absorbing K_3 radiation were removed we should not see, in the centre of the K line, either the sun's continuous spectrum from the photosphere, nor this after absorption in the K_1 layer. What we should see would be a bright line whose wings we know as K_{2V} and K_{2R}. How bright would be the centre of the K_2 line we do not know, but presumably it would not be less bright than the observed K_2 wings. Now the K_2 reversals vary enormously in brightness in different parts of the sun. Even over the undisturbed areas of the sun, K_2 is not uniformly bright as the Ca spectroheliograms show. The normal brighter and darker network in these photographs possibly appears with greater contrast than the actual variations of brightness of the K_2 line in quiescent regions of the sun. There is, however, no observation to suggest that the height of the chromosphere at the limb varies in a corresponding manner, a fact which is possibly due to the foreshortening of the close network at the limb of the sun. Besides this normal variation of the K_2 line in undisturbed regions of the sun, the K_2 line is very much brighter over disturbed areas of the sun, giving rise to the calcium flocculi. Indeed K_2 can be very much brighter than the undimmed continuous spectrum from the photosphere. So we see that the K_3 absorbing layer can be subject to radiation pressure which may vary between very wide limits over different parts of the sun. If the normal brightness of K_2 is just sufficient to support the chromosphere against gravitation, the brightest states must force the Ca^+ atoms above it completely away from the sun. Exact estimates must await photometric measures.

If the radiation supporting Ca^+ atoms comes from the K_2 layer as mentioned above, there will also be a further effect when the prominence ascends. As explained by Milne, an ascending prominence will absorb light from the wings of the Ca line owing to Doppler displacement of the absorption line. Owing to the K_2 reversals, however, the prominence will be subject to a decreasing radiation pressure as the absorption moves off the K_{2V} line. In undisturbed regions of the sun this minimum radiation is at about 0·26 A on the violet side of the centre of the line, corresponding to a velocity of ascent of about 20 km/sec, but in disturbed regions the minimum radiation will be only reached by greater velocities. Should this critical velocity be overshot, then the ascending prominence will be subject to an ever-increasing radiation pressure, as originally conceived by Milne, until the absorption is displaced beyond the K_1 wing.

Conclusions.—1. The comparison of photographs of prominences taken in calcium and in hydrogen light shows that the forms of quiescent prominences are essentially the same in these two elements, even to considerable detail. This is in agreement with the conclusions of other observers. Since radiation pressure can only exert an appreciable force on the atoms of Ca^+ and not on atoms of H, this evidence is not in favour of the theory of radiation pressure as the force supporting prominences.

2. Even in the case of eruptive prominences where the relative brightness in $H\alpha$ is generally less than in other types, the essential similarity of form and of height attained is maintained and the motion of ascent of Ca^+ atoms is also partaken of by the atoms of H. This evidence is also not in favour of the theory of radiation pressure as the propelling force in eruptive prominences.

3. The relative brightness of the calcium K line and of the $H\alpha$ line may vary in different prominences and even in different parts of the same prominence. Owing to the possible effects of Doppler displacements spectroheliograms cannot offer conclusive evidence as to whether these variations in brightness are really due to varying proportions of the numbers of Ca^+ and of H atoms.

4. Consequent on the conclusions 1 and 2 above it seems quite clear that whatever force raises Ca^+ atoms into prominences, and sometimes drives them away from the sun, is also acting, either directly or indirectly on hydrogen atoms also (and presumably on helium atoms as well). That radiation pressure on

Ca $^+$ atom is appreciable cannot be denied. Whether it is possible for Ca $^+$ atoms to be raised by radiation pressure into prominences and for other atoms to be carried along with Ca $^+$ atoms, by collisions or in some other way, is a subject for investigation, but if radiation pressure on Ca $^+$ atoms is the ultimate force lifting H and He atoms also, the weight to be supported by radiation pressure must take account of these atoms as well as those of calcium. It would not be of much help to find a new cause for supporting H and He different from that supporting Ca $^+$, since it is unlikely that any such effect would be just sufficient to support H and He to exactly the same height as radiation pressure does Ca $^+$.

5. It is shown that calculations of the radiation pressure on Ca $^+$ atoms must take account of the radiation in the reversals of the Ca $^+$ lines, but the effect cannot be exactly calculated until photometric measures are available.

KODAIKANAL,
21*st March* 1932.

T. ROYDS,
Director, Kodaikanal and Madras Observatories.

PARTICULARS OF THE REPRODUCTIONS IN PLATES I AND II.

All the photographs are positives. Figure 1 is reproduced on the same scale as the original and figures 2 to 15 are 3·9 times enlargements. One inch in figures 2 to 15 represents 3·5 minutes of arc, or 95,000 miles, or 152,000 km. The times given below are the times of transit of the centre of sun's disc and are in Indian Standard Time, (5½ hours fast on G.M.T.).

—	Date.	Extent.	Ca photagraph taken at		H photograph taken at	
			H.	M.	H.	M.
Fig. 1	1929, Feb. 27.	Entire limb.	8	0	8	26
Fig. 2	1930, Apr. 9.	13°SW to 35°SW.	8	34	8	25
Fig. 3	1929, Dec. 10.	40°SW to 57°SW.	8	56	8	41
Fig. 4	1930, June 11.	10°NE to 35° NE.	8	18	8	41
Fig. 5	1930, Apr. 23.	35°SE to 10°NE.	8	17	8	2
Fig. 6	1929, Sep. 12.	15°SW to 60°SW.	8	20	8	10
Fig. 7	1931, Feb. 7	15°SE to 27°NE	8	45	8	26
Fig. 8	1930, May 4	22°SE to 80°NE.	8	4	8	29
Fig. 9	1930, Feb. 5.	5°SW to 30°SW.	8	52	8	42
Fig. 10	1928, Dec. 15.	15°NW to 20°SW.	9	13	8	48
Fig. 11	1930, Feb. 6	18°SW to 43°SW.	7	54	8	12
Fig. 12	1929, Dec. 10.	7°SE to 15°NE.	8	56	8	41
Fig. 13	1929, Dec. 10.	5°NW to 20°SW.	8	56	8	41
Fig. 14	1929, Jan. 14.	10°NE to 35°NE.	8	45	8	29
Fig. 15	1930, June 24.	35°NW to 23°SW.	11	31	11	47

PRICE, 8 *annas*]   MADRAS: PRINTED BY THE SUPERINTENDENT, GOVERNMENT PRESS—1932.