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PHYSICAL CONDITIONS IN LIMB FLARES AND ACTIVE PROMINENCES

IV. COMPARISON OF ACTIVE AND QUIESCENT PROMINENCES

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ABSTRACT

Spectra of active and quiescent prominences appearing simultaneously at the limb of the sun are analyzed and discussed. The quiescent prominence shows a spectrum identical with that of the chromosphere at 1500 km, with strong lines of H, He I, and ionized metals and weak He II. The active prominence shows strong He II and very weak ionized metal lines The lines in the active prominence are very much broader The width of lines in either prominence is shown to depend on their excitation potential. It is proposed, as a result of many observations, that, except for strong lines such as those of hydrogen and Ca II, the spectra of prominences fall into two sharply defined classes, depending on whether they are "hot" or "cool "

I. INTRODUCTION

On March 23, 1959, a very active region was on the east limb of the sun. Its activity was marked by the occurrence at 0950 U.T. of a huge flare of importance 3+ with strong terrestrial effects. This flare and accompanying coronal and prominence phenomena are well described by Waldmeier (1958). Observations at Climax began shortly after dawn at 1419 U.T. and thus record only the declining phase of the flare activity. The record of the postflare (and possibly even unrelated) prominences is fairly complete. Some very interesting spectra were obtained. In addition, a large filament was seen at the limb; in subsequent days it rotated around to cover at least 90° in longitude. It was possible to make comparisons of spectra of the active prominences and the filament on the same spectrogram. These spectra have already appeared elsewhere (Zirin, Curtis, and Watson 1958) without detailed analysis. The striking difference in the spectra of the two objects is immediately apparent. They are shown in Figure 1. The reader is referred to the two papers mentioned above for more illustrations.

There really are two active prominences—one a low-lying mass of flare brightness (perhaps part of a loop), the other, a complex suspended loop which began forming around 1430. The spectra of both are identical except for slight differences in line width.

Table 1 gives the times and spectral coverage of the various spectra. At each time, about twenty spectra were taken at successive height intervals of 2300 km. Both 1-second and 10-second exposures were made. Low-dispersion spectra from Sacramento Peak were also available.

II. SPECTRA

a) *Intensities*

The interesting features of the spectra may be summed up rapidly. The quiescent shows a large number of ionized metallic lines, neutral helium, and hydrogen lines. The active prominence shows no metallic lines, but the He I lines are still present, and the He II line λ 4686 is quite strong. In particular, although the λ 4713 line is much stronger than the λ 4686 line in the quiescent, it is weaker in the active prominence. This strengthening of λ 4686 in active prominences is quite characteristic.

Waldmeier reports essentially the same phenomenon in the spectral region he observed. Although the quiescent prominence showed every normal prominence line in the

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5167–5400 A region, no lines could be seen in the active prominence except for the Mg B lines and the 5412 line of He II. Waldmeier also notes the appearance in the active prominence of the He I lines 5876, 6678, and 7065, and the Na D lines. Many people have wondered at the appearance of the low-excitation Na D lines in a high-excitation object. It seems likely that we see them mainly because they are very strong resonance lines and also because all the Na is in the form of Na II (ionization potential 47 ev). The latter effect is important because the Na I abundance is proportional to $N_e \cdot N$ (Na II). Since there is almost no Na III, all the sodium is Na II, and the Na I concentration is therefore greater than if the second stage of ionization were easily accessible. Quantitative calculations on the Ca II and Na I equilibrium are badly needed; we have some preliminary calculations that indicate that, in a typical prominence, the K line remains optically deep (and hence bright) up to around 50000°. The weaker metallic lines, of course, fade out very quickly with increasing temperature.

TABLE 1

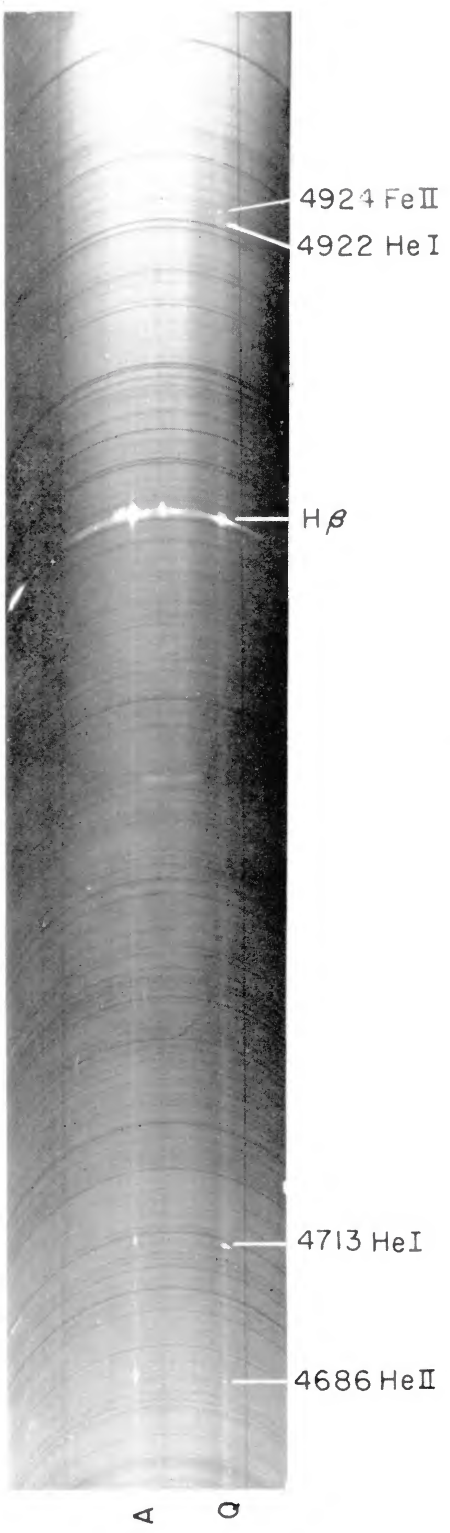
RECORD OF OBSERVATIONS

Time (U T)	Exposure (sec)	Wave-Length Region	Remarks
1419 1422	10 1	λ 3850–λ 4120	Quiescent only; loops very faint
1448 1452	10 1	λ 4450–λ 4950	Bright loops+continuum
1519 1523	10 1	λ 3850–λ 4120	Same λ 4086 present
1537 1540	10 1	λ 4450–λ 4950	Everything somewhat fainter
1552	8	λ 5300–λ 5800	Yellow line present in prominence areas

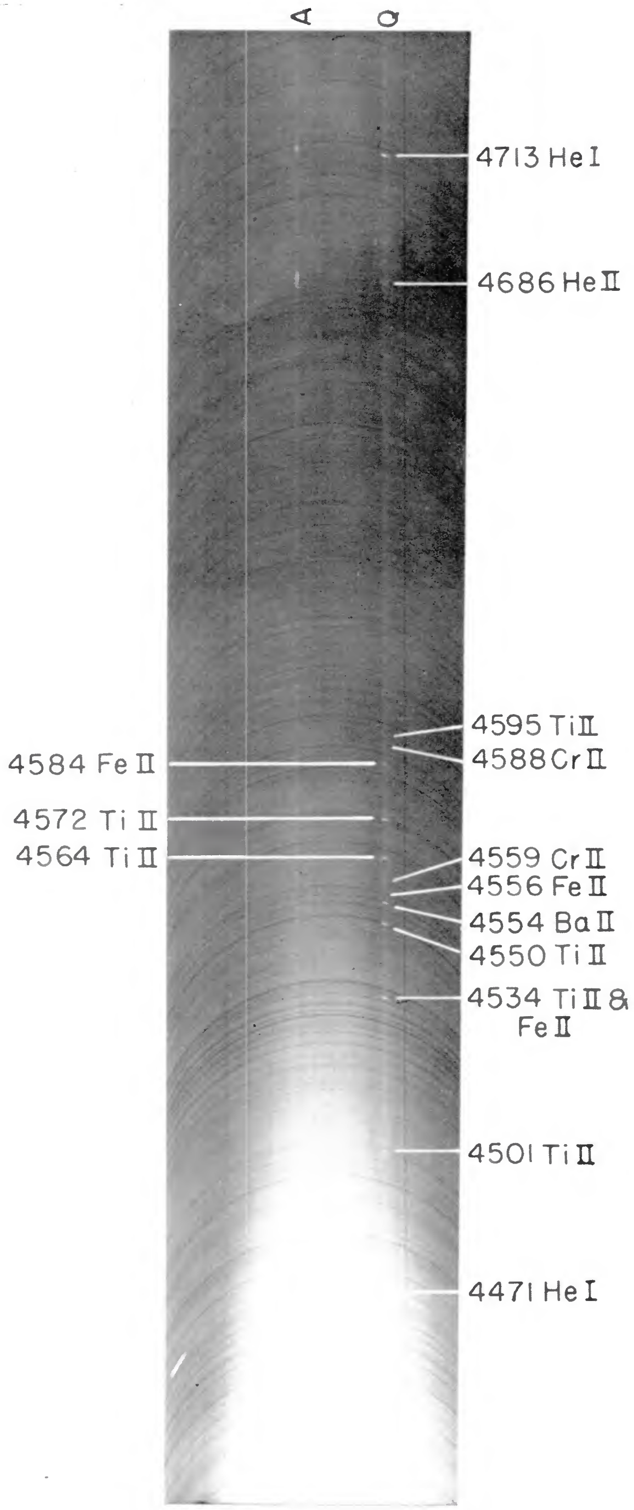
A similar phenomenon is also noted by H. J. Smith (1957). In his description of the spectra of three prominences, it is seen that in the loop prominence (γ 3862) the intensity of all the weaker metal lines is considerably reduced, and only an He II-He I-H-resonance metal lines spectrum remains.

The spectrum of the quiescent prominence is exactly that of the chromosphere at 1500 km. This height is set by the ratio He I 4713 : Ti II 4572, using the data given by Athay and Menzel (1956) and by Zirker (1958). The ratios of the metals to one another do not change appreciably in the chromosphere; hence the height of comparison is determined by the He I : metals ratio. At 1500 km the He : metals ratio changes very rapidly, so that a considerable range of λ 4713 : λ 4572 would match this height. Table 2 gives the intensities of the lines observed in millionths of the intensity of the photosphere at 4700 A. The first three columns give the identification (wave length, ion, multiplet number). Then the intensities in the active and quiescent prominences are given, and, finally, chromospheric intensities from the two sources noted above for 1500 km, multiplied by a factor to make the values for 4713 in chromosphere and prominences the same. The ratios in the quiescent and the chromosphere are seen to be the same. There appear to be no anomalies in the intensities of the metallic lines relative to one another. The values for the very strong lines of hydrogen and calcium are not particularly accurate.

The spectra of the two active prominences (low-lying flare and high incipient loop) a


4924 Fe II
4922 He I
Hβ
4713 He I
4686 He II
A
Q

b


A
Q
4713 He I
4686 He II
4595 Ti II
4588 Cr II
4584 Fe II
4572 Ti II
4564 Ti II
4559 Cr II
4556 Fe II
4554 Ba II
4550 Ti II
4534 Ti II & Fe II
4501 Ti II
4471 He I

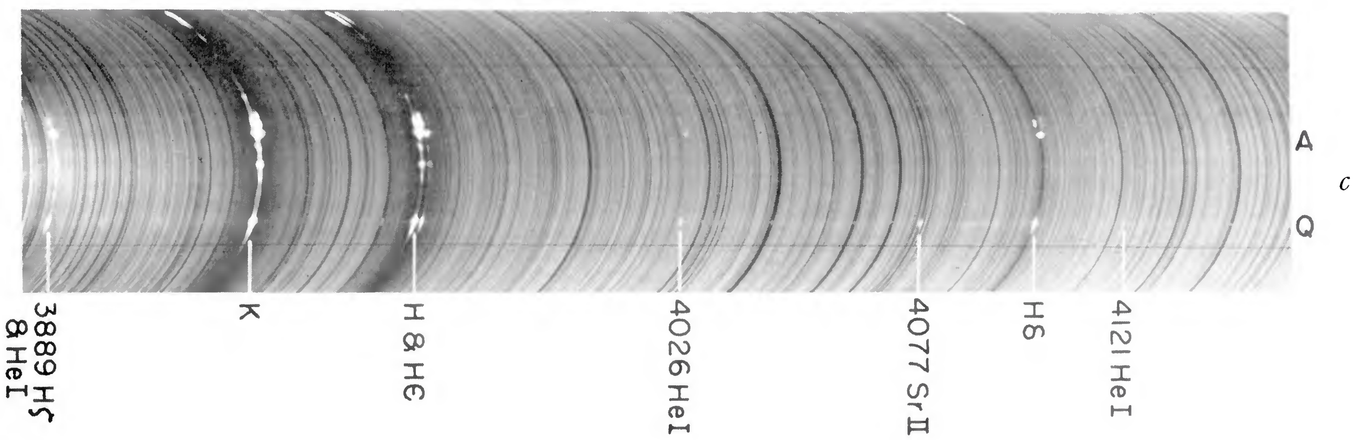


FIG. 1.—Spectra of quiescent and active prominences, *A:* active; *Q:* quiescent. *a*, 4650–4950 A; *b*, 4400–4750; *c*, 3880–4200 A, 1519 U.T. Overlapping prints of one spectrum height 9000 km above photosphere, 1448 U.T.

TABLE 2

LINE INTENSITIES* IN PROMINENCES AND CHROMOSPHERE

λ	Ion	Multiplet No	Active	Quiescent	Chromo-sphere
4924	Fe II	42	. . .	201	NV
4922	He I	48	195	47	60
4861	Hβ	1	15000	15000	28000
4713	He I	12	116	102	102
4686	He II	1	175	27	30
4590	Ti II	50		12	NV
4588	Cr II	44		18	NV
4584	Fe II	38		27	32
4583	Ti II	39		1 4	NV
4583	Fe II	37		3 4	NV
4576	Fe II	38		1 4	NV
4572	Ti II	82		77	101
4571	Mg I	1		14	NV
4564	Ti II	50		64	72
4559	Cr II	44		13	25
4555	Cr II	44		tr	NV
4554	Ba II	1		61	NV
4550	Ti II	82		81	114
4534	Ti II	50		68	117
4523	Fe II	38		4	91
4520	Fe II	37		tr	NV
4515	Fe II	37	. . .	tr	NV
4508	Fe II	38		7	NV
4501	Ti II	31	. . .	66	107
4471	He I	14	800	1400	960
4468	Ti II	31		65	NV
4444	Ti II	19		40	112
4144	He I	53	64	32	NV
4121	He I	16	64	51	32
4101	Hδ	1	5000	7000	10000
4087	Ca II	10	. . .	8	NV
4086	Ca XIII	1F	56	. .	NV
4078	Sr II	1	46	673	850
4072	Fe I	43		34	28
4064	Fe I	43		41	38
4046	Fe I	43		87	78
4034	Mn I	2		20	18
4032	Mn I	2		24	25
4031	Mn I	2	. .	33	25 (?)
4026	He I	18	315	300	236
3970	Hε	1	1000	1200	NV
3969	Ca II	1	15000	15000	60000
3965	He I	5	56	33	59
3962	Al I	1		78	129
3944	Al I	1	. . . .	15	39
3933	Ca II	1	15000	15000	60000
3913	Ti II	34		40	NV
3900	Ti II	34	. . .	28	NV
3889	Hζ	1	150	1000	6000
3888	He I	2	150	1000	

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* Intensities in active and quiescent are given in 10^{-6} of 1A of photosphere at the same wave length. Chromosphere intensities are arbitrarily normalized so as to give equality with 4713, to facilitate comparison. "NV" means no value given by Zirker and means the line is too faint to be measured

are exactly the same, and thus only one set of ratios is given. These spectra are, furthermore, exactly the same as the spectra of every loop, surge, or flare that we have ever observed (about twenty-five cases). It is quite remarkable that the scatter in line-intensity ratios is small among these objects, even though these ratios differ greatly from those in quiescent prominences.

We have one set of spectra of an eruptive prominence (*disparition brusque*) taken on May 15, 1959. This shows precisely the same spectrum as the quiescent prominence discussed here, even though the lines are greatly broadened by macroscopic motions.

The behavior of the coronal lines is interesting. Waldmeier shows that the yellow line appeared only in the regions of the two hot prominences. Our observations confirm this. He observed brightening of λ 5694 at the position of the loops at 1334 U.T., just a little while before their formation began around 1430 U.T. Our observations of λ 4086 (Ca XIII) show nothing at 1419 U.T., which seems to contradict his observation. However, λ 4086 is more difficult to observe than λ 5694, and this must be the explanation. Our observations at 1519 U.T. show the λ 4086 coronal line quite plainly, which is a good indication that this coronal line strengthened simultaneous with the development of the loops.

TABLE 3

AVERAGE HALF-INTENSITY WIDTHS $2\Delta'\lambda/\lambda$

		Quiescent	Active
Metals		$0\ 41\times10^{-4}$	
He I	4922	$0\ 53\times10^{-4}$	$2\ 8\ \times10^{-4}$
	4713	$0\ 67\times10^{-4}$	$3\ 2\ \times10^{-4}$
	4471	$0\ 83\times10^{-4}$	
	4026	$0\ 84\times10^{-4}$	$2\ 2\ \times10^{-4}$
	Arg.	$0\ 72\times10^{-4}$	
He II	4686	$1\ 20\times10^{-4}$	$4\ 0\ \times10^{-4}$
H	β	1 51 (self-abs)	$1\ 85\times10^{-4}$
	δ	1 42 (self-abs)	
	ϵ	1 07	

b) *Line Widths*

Although the line intensities of the two prominences studied here tell a very orderly tale, the line widths of each prominence show a rather disorderly pattern. That is, the lines in the active are all very much broader than those of the quiescent; but in each group there is some confusion. The values of $\Delta\lambda/\lambda$, with instrument broadening removed, are given in Table 3. Again, as no difference was found between the low and the high active prominences, they are given as one. The measurement of line profiles is rather difficult, as the slit of the microphotometer must be accurately positioned on the small image of the emission line. Line widths, however, turn out to be relatively insensitive to errors of position. The line widths given are the averages of repeated measurements on each of a number of spectra at various heights. The internal scatter of these measurements was low. The probable error of line-width measurements on the quiescent is around ±10 per cent; on the active, twice as much.

The quiescent prominence shows fairly reasonable line widths. The metallic lines are all quite narrow, and all give the same small half-width. Thus all are lumped together in Table 3. The He lines are broader, and the hydrogen lines broader still. Measurements of the He and H lines showed some scatter, and the best determinations were chosen. In particular, measurements of λ 4713 showed very little scatter in the measurements on many spectra; hence great weight is given to the observed width of this line.

If we assume that all lines come from the same region, with one temperature, we may apply the formula

$$T = 1.95 \times 10^{12} \left(\frac{1}{M_1} - \frac{1}{M_2}\right)^{-1} (W_1^2 - W_2^2) ,$$

where $W = 2\Delta'\lambda/\lambda$, and get the following results

H+He (using Hδ and He av.)	16000°	4713+metals	24000°
H+metals .	19500°	He II+metals	108000°
He+metals .	30000°		

We see that we have the same result as was found in Papers I and III for hot prominences (Tandberg-Hanssen 1959; Tandberg-Hanssen and Zirin 1959); the high-excitation lines appear to originate in regions of higher temperature than do the low-excitation lines.

In the active prominence the same effect is noted. The λ 4686 line is clearly broader than λ 4713. Since these lines are very close in the spectrum and of about the same intensity, there is little likelihood of error in this conclusion. The width of the λ 4686 line is greater than any we have yet measured, being almost 2 A. If there were no broadening by macroscopic motions, this would indicate a temperature around 1400000°. The λ 4922 line is about as broad as 4713, but the strong helium lines λ 4026 and λ 4471 show widths of only about 1 A or less. This would indicate that these strong lines tend to come from somewhat cooler regions, as already suggested by one of us (Zirin 1957). It is clear from the spectra that λ 4686 and λ 4713 come from a small region of the active prominence showing strong continuum, while the λ 4026 and λ 4471 lines appear to come from a more extended region. The half-widths of the hydrogen lines vary from line to line because of self-absorption; and from height to height as well, perhaps for the same reason. A characteristic value for Hδ is 0.7 A. No value is as great as the He widths. Thus the results parallel those for the quiescent.

One must admit, therefore, that there is at present no definite way to determine the precise temperature of either the hot or the cool prominences. The evidence is that lines of different excitation come from different regions, so that there is no single temperature which may be assigned. Further, exact temperature determinations by intensity ratios become meaningless because the lines do not necessarily come from the same region. One must rather turn to the question "What are the physical conditions which give rise to the spectrum observed?" The spectra of hot and cold prominences are so different that this question is meaningful; the fact that there are two and only two different types of spectra makes research in this direction promising.

One can, perhaps, assign approximate temperatures which might hold for the preponderance of the material in the prominences. This would be around 10000° for the cool prominences and 50000° for the hot ones. This is not, of course, the temperature of all the material.

III. CONCLUSIONS

The work reported here shows that material in the solar atmosphere falls into certain sharply defined spectroscopic classes. These are shown in Table 4. Class I is not defined by the present work and is included only for completeness. The identification of the spicules as Class III phenomena is based on extrapolation of eclipse data to the height (~6000 km) at which spicules are observed.

The similarity of flare spectra to loop and surge prominence spectra is confirmation of the point made by Waldmeier and others that flares seen in projection appear as bright loops or surges. There seems to be no alteration of the spectrum except for a general increase in intensity of all lines.

We must here take issue with the statement of de Jager (1959) that the 4686 line is usually absent from flares. This line is monotonously present and enhanced on every flare spectrum we have obtained. The same is true of the flare reported by Jefferies, Smith, and Smith (1958). Waldmeier (1949) notes enhancement of He II 5412 (normally a companion of 4686) in flares. The negative result of Krat and Sobolev (1958) upon which de Jager bases his remark must be ascribed to the fact that they were principally looking at disk flares, where the high background precluded seeing the He II lines, which are much fainter than the hydrogen lines.

Superficially, the differences in spectrum noted here are easily explained. The high temperature of the hot prominences raises the metals to higher stages of ionization whose strong lines are not readily observable. The same increase in temperature increases the strength of the He II lines but does not affect the He I lines, as they are somewhat insensitive at these temperatures. In this connection a search for lines of Fe III, Ti III, etc., appears in order. In particular, the Fe III line 4420 might appear in a very bright flare and is worth looking for.

On the other hand, there is no apparent explanation for the fact that there is no intermediate spectral class between Classes II and III. Either 4026 is equal to 4077, or it is ten times stronger. Athay and Thomas (1956) proposed that chromospheric material was in thermal equilibrium only at two specific temperature plateaus at which the unknown heat input to the chromosphere is balanced by emission of H and He II in turn. The problem here is that the material is not at a specific temperature, but a range of temperatures, so that, although the basic principle set forth by Athay and Thomas is valid and important, a more sophisticated solution is necessary. We have discrete sets of physical conditions rather than discrete temperatures. That the range of temperatures is real is based on more than the line widths given here alone. A number of analyses of the equilibrium of He (Zirin 1957; Athay and Johnson 1959) indicate that the observed He I and He II emission in quiescent prominences cannot be explained by temperatures much less than 30000°.

TABLE 4

SPECTRAL CLASSES IN THE SOLAR ATMOSPHERE

	CLASS			
	I	II	III	IV
Criteria	Strong metals Weak He	$\lambda 4026 \sim \lambda 4077$ $4572 \sim 4713$ $4713 >> 4686$	$\lambda 4026 >> \lambda 4077$ $4713 >> 4572$ $4713 \sim 4686$	Coronal lines
Examples	Low chromosphere	Chromosphere ∼ 1500 km Quiescent prominences *Disparitions brusques*	High chromosphere (spicules) Loops and other active prominences Surges, Flares	Corona

It is no doubt significant that the Class III prominences are all short-lived phenomena and the Class II prominences relatively long-lived. Flares, surges, and spicules are transient, and loop prominences condense out of the corona and rain down rapidly, even though a display of loops will last for hours. The low chromosphere appears fairly static, and filaments last many days. The *disparitions brusques* must be regarded as a phase in the long life of a filament; it is clear from the data given here that the *disparition* is not due to heating but to a dynamic, probably magnetic, effect. Although projection effects make it impossible to say that we see surges at the exact moment of emergence, it appears that they are already hot when they leave the surface and may therefore be the result of a superheating in the surface layers.

It is possible that the temperature range observed in a single prominence is the result of a very fine filamentation. In a loop prominence, material is presumably continually cooling, and at any one time we see a number of filaments in different stages of cooling. This is especially probable in view of the small scale of our spectra. Continuity requires that the intensities of He I and He II lines always be in roughly the same proportions, as long as the cooling rate is roughly the same for the different filaments. After the gas cools the Hα-radiating stage, further cooling is not possible because it does not radiate the conducted coronal heat efficiently enough. This temperature (around 30000°) is still far too hot for the weaker metallic lines to be seen, although the strong resonance lines appear. Two facts must be remembered: the hydrogen lines are strongly radiated over a great range in temperature, from 5000° to 50000°; and the radiation per cubic centimeter, in the loop prominence as well as the electron density, is much greater than that in the quiescent. In the present case the quiescent is very much larger than the loops, and we look through a tremendous path length in the former; yet the Hβ intensities and the Thompson scattering by electrons in both are about equal. Finally, the reason why surges, which are morphologically a completely different phenomenon, should show the same He I: He II ratio as loops is not clear at all.

Quiescent prominences are even less well understood than active ones, and, since we know nothing about what maintains their temperature or their relations with the corona, it is difficult to say why they show the spectrum that they do. There is some possibility that they too condense from the corona. In general, the quiescents correspond to minima in the coronal brightness distribution; but the coronal intensity there is not zero. The prominences are so long-lived that it is impossible to see how the observed temperature variations are maintained unless they are the locus of a continuous slow condensation from the corona. One might explain the weakness of 4686 by the fact that the He II phase goes very rapidly, since there is little coronal heating, and thus we see little of it at any one time.

The reader has probably noted that little has been said about the stronger emission lines, such as the Balmer lines, H and K of Ca II, etc. To the best of our knowledge, these do not show the strong changes apparent in the weaker lines, although small effects have been noted (Waldmeier 1951; Newkirk 1956). Perhaps this is because these lines are generally self-absorbed and large changes in physical conditions would be necessary to change their intensity even slightly.

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