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Subject: On the Enhancement of Certain Helium Lines in the Limb Flare of 24 June 1956.

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ABSTRACT

An unusually well observed limb flare occurred on 24 June, 1956. The lines 4471, 4713, 4922 and 6678 of neutral He, 4686 of ionized He, and Hα and Hβ appear strongly in the spectra. The intensities of 4471, 4686, 4713 and 4922 are about equal. The temperature of the flare is deduced by comparing the Doppler half-widths of the helium and hydrogen lines, and, more accurately, from the relative intensities of 4686 and 4471. Both methods give roughly 30,000 degrees.

The anomalous excitation of 4713 and 4922 are studied in terms of the helium equilibrium. It is found that at high temperature and densities these lines, as well as certain other helium lines, are strongly excited relative to 4471 and 5876 by collisions from the 1^1S ground state of helium. The conditions necessary are $T_e > 30,000$ degree and $N_e > 3 \times 10^{12}$.

I. OBSERVATION

On 24 June, 1956, 1305 UT, a flare occurred in an active region on the west limb of the sun. This flare was coincident with a sudden short wave fadeout of importance 3-, although the flare was classified only as importance 1-. Classification of flares at the limb is difficult, but it appears that the event was a large one. The flare was well observed at Climax and at Sacramento Peak, with a series of spectra at graded heights being obtained at the former, and direct cinematograms in Hα at the latter. A sudden cosmic noise absorption (SCNA) was observed in Boulder starting at 1257 UT, and a sudden enhancement of atmospherics began at 1300. The SCNA produced a maximum absorption of 22% at 1303 UT. This is quite a high value for the time of day (0603 MST).

*Figure 1 is a series of Hα photographs depicting the progress of the flare. The spectra obtained at Climax cover the region Hα -6678, and the region 4400- 5000 A. In the latter region, spectra were obtained at five graded height intervals of 4500 km each above the limb. Some of

*Figures 1 and 2 have not been reproduced here but will appear in the final paper.

these spectra are reproduced in Figure 2. All the spectra were standardized by means of the solar disk itself. However, the precise attenuation of the filter used is not accurately determined as yet, so the listed absolute values (in terms of the intensity of the solar continuum) are only nominal. The relative photometry of the lines is quite reliable. On the other hand, certain inconsistencies point up the fact that we do not always look at precisely the same point of the solar atmosphere with different wave lengths.

The most striking feature of the spectra obtained is the strong relative enhancement of the helium lines in the flare. The lines 4471, 4713, 4922 and 6678 of neutral helium are all quite strong relative to D3 and Hα, as is the 4686 line of ionized helium. The occurrence of 4471, 6678 and 4686 has been noted many years ago. Table 1 shows the relative intensities of helium lines referred to 4471 as measured by: Column 1, Richardson and Minkowski (1939) in flares; Column 2, Athay and Menzel (1956) in the chromosphere; and Column 3, the present work. Comparison of the first two columns shows that 6678 had already been noted as enhanced in flares relative to the other helium lines. The increased intensity of the lines 4713 and 4922 has not, to my knowledge, been observed before. *One purpose of the present paper is to elucidate the physical conditions that give rise to this phenomenon.

Figure 3 shows a simplified energy level diagram for helium, on which the important lines, together with their spontaneous transition probabilities, appear. Under normal conditions of excitation, the triplet helium lines should have relative intensities given by: (a) their transition probabilities, multiplied by (b) Boltzmann distribution factor corresponding to 6000°K, times (c) a dilution factor of $\frac{1}{2}$ (Jefferies 1955, Zirin 1956a). Thus lines originating at levels of the same excitation potential should have relative intensities equal to their relative statistical weights multiplied by their relative transition probabilities. If we had a pure recombination spectrum, then the intensities would be proportional to the statistical weights only. For example, the relative intensities of 4471 and 4713 would be $\frac{15}{3} \times \frac{15.7}{4.6} = 17.1$ in the first case, and $15/3 = 5$ in the second. The relative intensity obtained by Athay and Menzel in the chromosphere is 13.7.

The four helium lines appearing on the spectra in the Hβ region have been measured on the recording microphotometer of the High Altitude Observatory, along with Hβ. The intensities obtained are presented, along with the measured half-widths, in Table 2. Designations a and b

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*The same intensification of helium lines appears on spectra just recently obtained (12 November 1956) at Climax. These spectra show the strongest yellow line (λ 5694) yet recorded at Climax, as well as the rare λ 5445 coronal line. In loop prominences at the same point on the limb, λ 4686 and λ 4713 appear as strong as, or stronger than λ 4471. There also appears a prominence line at 5411.5 A, which is due to the 7→4 (Brackett γ) transition in ionized helium. These spectra are presently being analyzed.

TABLE 1

RELATIVE INTENSITIES OF HE LINES IN FLARES AND IN THE CHROMOSPHERE

λ	Richardson & Minkowski Flare	Athay and Menzel Chromosphere	Zirin Flare
4471	1	1	1
4686		.021	1
4713		.073	1
4922		.056	1
5876	3	11.8	
6678	2	.31	>5

TABLE 2

LINE INTENSITIES AND HALF-WIDTHS IN THE JUNE 24th FLARE
(Intensity in nominal units 10-3 solar continuum at Hβ)

GH\\λ	4471	4686	4713	Hβ	4922
1	23.8 .59A	32.8 .82A	23.2 .74A	in spill	in spill
2	134.4 .95A	151 1.08A	151 .75A	in spill	in spill
3	in spill	65 .66A	42.2 .69A	1080 1.77A	99.8 .74A
3a*	- -	33 1.75A	18 1.80A	2820 2.75A	
4	646 .44A	<1	< 1	130 .82A	
4a*	128 .92A	3.4	2.6	879 1.07A	133 .82A
Chromosphere	13.7	0.29	1		0.77

*Refers to a different position angle, same graded height refer to different position angles at the same height. The intensities are given on an arbitrary scale, but one unit equals roughly 2.4×10^{-5} of the solar continuum at that wave length. Chromospheric intensities are from the paper of Athay and Menzel. Measurements of 6678 were also made, but it was unfortunately somewhat overexposed. On the fifth graded height step of the 6678 series its intensity is greater than 0.085 of the solar continuum. Allowing for the difference in continuum intensities, we conclude that 6678 is at least twelve times brighter than 4471 in this flare.

One very interesting point is apparent from the Table and from Figure 2. In the fourth graded height step the Hβ emission comes from two position angles; at one, the profile is broad, at the other, narrow. The 4922, 4713 and 4686 lines are only evident at the position angle of the broad Hβ feature, and there they show broad but faint emission. The 4471 behaves very differently. It shows a broad feature corresponding to the other helium lines, somewhat brighter than them; but it shows a much stronger feature corresponding to the narrow Hβ emission. Thus the 4471 emission seems to be stronger in the cooler part of the flare.

Of course, this points up an unresolved difficulty that we always face, namely that we are never sure the different emissions come from the same region of the flare or prominence we are studying. On the other hand, if their two dimensional extent is the same, it is reasonable to assume the third dimension to be similar as well.

Although unfortunately the Hβ emission lines are denser than the most dense standard on all the spectra, it is possible to extrapolate the characteristic curve, which is fairly straight in this region, and obtain a rough profile. I did so and fitted this profile with a Doppler profile, including damping and self-absorption. A good fit is obtained for graded height 3a with a τ of 3.3 at the line center and a Doppler half-width of 1.05A. This value, when compared with the helium half-widths at this point gives a kinetic temperature of 39,000 degrees. Of course, this value is subject to errors, but we shall later see that these errors are probably not too serious.

II. THEORETICAL INTERPRETATION

Now we are to explain the anomalous relative intensities of these lines. We know the flare is hot from the Doppler profiles and the appearance of 4686. We can, in fact, get a very good measure of the temperature from the intensity of 4686, since this is very sensitive to temperature. We therefore calculate this intensity first.

To calculate the 4686 intensity and its ratio to other helium lines we need a model of the neutral helium equilibrium. This has been calculated by Jefferies (1955) and by Zirin (1956a). The former calculation neglects photoionization and collisional ionization from the upper triplets, which leads to occupation numbers for the triplets which are too high. The latter has a numerical error in the calculation of $C_{100-201}$, and also leaves out collisional ionization from the triplets, an effect that becomes

TABLE 3a

RATIO OF N_I/N_{II} OF NEUTRAL TO IONIZED HELIUM

T_e (10^4)	1.0	1.5	2.0	2.5	5.0	10.0	20.0
N_I/N_{II}	$.287 \times 10^6$	294	8.51	0.624	3.75×10^{-3}	1.32×10^{-4}	1.23×10^{-5}
N_{II}/N_{III}				2.7×10^6	7.7	0.012	$.77 \times 10^{-3}$

TABLE 3b

OCCUPATION NUMBER OF THE 2^3S STATE OF HELIUM

N_e / T_e	10^{11}	5×10^{11}	10^{12}	5×10^{12}	10^{13}	cm^{-3}
1.0×10^4	3.95×10^{-7}	1.975×10^{-6}	3.26×10^{-6}	9.6×10^{-6}	12.6×10^{-6}	$N_e N_{II}$
1.5×10^4	3.03	1.34	2.32	5.7	7.0	
2.0×10^4	2.36	0.94	1.62	3.39	3.93	
2.5×10^4	1.71	0.68	1.07	2.00	2.25	
5×10^4	0.730	0.26	0.384	0.615	0.67	
10^5	0.229	0.0765	0.108	0.161	0.172	
2×10^5	0.119	0.0396	0.0561	0.0835	0.0894	

important at the high densities of flares. These defects have been remedied in Table 3, which gives N_I/N_{II} (neutral: singly ionized), N_{II}/N_{III} (singly ionized: doubly ionized) and $N(2^3S)$ for various densities and temperatures.

Now 4686 can be excited in two probable ways, viz.: by recombination from He III, and by photoexcitation from the ground state (the rate of collisional excitation is slow). In a recent note (Zirin 1956b) I calculated the 4686 emission by the first process. R. G. Athay pointed out to me that the intensity of 4686 in the chromosphere is so great that it must be excited by the second process. Reflection immediately shows this to be the case, for at almost any temperature above 15,000 degrees there is enough He II for the gas to be optically deep in the 1^2S-4^2P transition. Then the occupation number of the upper level of 4686 will be given by a Boltzmann distribution, with an excitation temperature equal to the kinetic temperature, viz:

$$N_{41\frac{1}{2}} = 3 e^{-51 \text{ e.v.}/kT} N_{10\frac{1}{2}} \tag{1}$$

where the subscripts give the n, L, and S of the levels in question. Since almost all the He II is in the ground state, $N_{10\frac{1}{2}} = N_{II}$. The spontaneous transition probability for 4686 will be the sum of the A's to 3^2S and 3^2D, and is 0.528×10^8. Therefore the emission of 4686 photons per cm^3 per sec is

$$F_{4686} = 1.584 \times 10^8 e^{-51 \text{ e.v.}/kT} N_{II} \text{ cm}^{-3} \text{ sec}^{-1} \tag{2}$$

This quantity is set forth in Table 4. Jumping ahead, we can compare it with the intensities of the other He lines, which we calculate below, and which are in Table 5. We note that the temperature of our case must be around 30,000 degrees. The 4686 emission varies so violently with temperature (even more than is shown, for N_{II} is increasing too) that this determination must be relatively insensitive to errors in the physical constants, so long as the physical model adopted is correct.

Having fixed the temperature of our flare, we now can look for the reason for the enhancement of the various lines mentioned. To find this we need go no farther than the experimental work of Lees (1932) and Thieme (1932) on the excitation of helium by electron collisions. The cross-section for excitation of 4713 is outstandingly strong, more than twice that for excitation of 4471. This is because the exchange process that makes the transition from singlets to triplets possible has a strong maximum for low electron energies, which makes angular momentum transfer unlikely. The cross-section for excitation of 4922 is about one-half that of 4713, but the maximum is much wider (plotted vs. energy).

TABLE 4

EMISSION OF 4686 PHOTONS ($cm^{-3} sec^{-1} N_{II}^{-1}$)

T_e (10^4)	1.0	1.5	2.0	2.5	3.0	3.5	5.0	10	20
F_{4686}	3.09×10^{-18}	1.11×10^{-9}	2.22×10^{-5}	7.92×10^{-3}	0.440	7.25	1140	4.26×10^{5}	8.24×10^{6}

The rate of collisional excitation of 4713 can easily be computed (using the cross-section measured by Lees) using an expression very similar to that given for $C_{100-201}$ in my earlier paper (Zirin 1956a). It is

$$C_{100-401} = 6.9\times10^{18}\, T^{-3/2} \alpha^{-2} (\alpha E_0 + 1)\, e^{-E_0/kT} \tag{3}$$

where E_0 is the excitation potential, and

$$\alpha = \left(\frac{1}{kT} + \frac{1}{4\times10^{-11}}\right)$$

And the rate of emission of 4713 is:

$$F_{4713} = N_e N_{100} C_{100-401} + \tfrac{1}{2} N_{201} e^{-7.5} A_{4713} \tag{4}$$

the second term being the normal excitation of 4713 from 2^3S. This rate is tabulated in Table 5. For N_e and T small, the second term predominates, and vice versa.

The rate of excitation of 4922 is given by a formula very similar to equation (3) except that the maximum of the cross-section curve is so broad that $\alpha \sim \frac{1}{kT}$ and we have

$$C_{100-420} = 6.67\times10^{-14}\, T^{1/2} (E_0/kT + 1)\, e^{-E_0/kT} \tag{5}$$

The rate of emission of 4922 is

$$F_{4922} = N_e N_{100} C_{100-420} + N_{ex} A_{4922} \tag{6}$$

where the second term denotes the fact that the line is also excited by other sources (e.g., from the other singlet states) which we really cannot estimate accurately. If we use just the first term, the rate differs only by a factor 2 from F_{4713}, therefore there is no point to tabulating it.

The rate of emission of 4471 is given by a simple formula, as it is excited principally by the 6000 degree photospheric radiation with a dilution factor $\frac{1}{2}$. Thus the emission due to this process is the Boltzmann factor times N_{201} times the spontaneous transition probability. To this we add collisional excitations from 1^1S, which will be at a rate half that of 4713, which we have already calculated. Therefore

$$F_{4471} = 15.7\times10^{6}\, e^{-7.51} N_{201} + N_e N_{100} C_{100-421} \tag{7}$$

This is tabulated in Table 5.

TABLE 5

EMISSION OF 4471 AND 4713 (PHOTONS/cm^3/sec/H II ion)

N_e / T_e	10^{11}	5×10^{11}	10^{12}	5×10^{12}	10^{13} cm^{-3}
1.0×10^4	0.43×10^{-3}	0.21×10^{-2}	0.36×10^{-2}	1.19×10^{-2}	1.6×10^{-2}
1.5×10^4	5.06 0.41	2.28 0.19	3.94 0.34	9.9 1.1	12.6 1.8
2.0×10^4	3.94 .47	1.65 0.21	2.86 0.40	6.42 1.54	8.07 2.80
2.5×10^4	2.86 .41	1.21 0.18	1.93 0.33	4.03 1.30	5.14 2.43
5.0×10^4	1.22 .32	0.512 0.149	0.796 0.287	1.81 1.30	2.67 2.56
10^5	0.382 0.113	0.257 0.053	0.237 0.102	0.554 0.472	0.856 0.929
2.0×10^5	.199 .033	0.073 0.014	0.107 0.027	0.205 0.113	0.281 0.219

From Table 4 we see the physical conditions under which the emission from 4713 and 4471 are roughly equal. The 4713 emission increases with temperature and linearly with density, up till the temperature where N_{100} has become very small. The 4471 emission falls off with temperature. It increases with density up to the point where collisional ionization of the triplets becomes important, and after that it is independent of density. Thus at higher temperatures and densities the 4713 emission catches up with the 4471 emission. Unfortunately, the broad range of conditions under which we get equal intensities means that we can only set lower limits to temperature and density. This limit would appear to be 25,000 degrees in temperature and about 2×10^{12} in electron density. Since, however, we can fix the electron temperature accurately in two ways, viz., by Doppler profile and by the 4686 emission, we can also fix a lower limit for the density in the flare. In our case the lower limit is around 5×10^{12}, for T_e is evidently 30,000 degrees.

From the considerations discussed here, it is possible to predict the relative enhancement of other helium lines in flares and hot prominences. The 3^3P-3^3S transition, λ 3889, was found by both Lees and Thieme to have a very high excitation cross-section. The former finds this cross-section 3.5 times that for 4713, the latter finds a factor 45. Therefore, the radiation in 3889 must be much enhanced. The same may be said, to a lesser extent, for other lines with appreciable excitation cross-sections. Some of these are: the lines originating from ^3S states: 7065, 4121, 3867; lines from ^1P states, such as 5016 and 3964; lines from ^1S states, like 5047 and 7283; and lines from ^1D states, such as 6678 and 4387, as well as 4922, already mentioned.

A partial confirmation of the prediction concerning 3888 is evident from the work of Athay and Orrall (1956). They measured the line intensities in a moderately hot, dense prominence observed at the eclipse of 1952. Their intensities for certain lines of interest appear below in Table 6.

TABLE 6

INTENSITIES OF PROMINENCE LINES (AFTER ATHAY AND ORRALL)

λ	4861	4340	4102	3889	3835	3800	5876	4471
Ident	$H\beta$	$H\gamma$	$H\delta$	H8	H9	H10	D3	
Log E	14.66	14.32	13.99	14.12	12.91	12.71	14.46	13.60

If we interpolate between $H\delta$ and H9, there is no doubt that log E for H8 must be less than 13.2, so the intensity measured is almost wholly that of 3888 of helium. This gives the ratio 3888 : 4471 : D3 as 1 : 0.4 : 2.9. In the chromosphere Athay and Menzel find 1 : 1.2 : 10. Thus 3888 is enhanced by a factor 3. Athay and Orrall suggest that the temperature of the prominence is about 20,000 degrees and the density, 2.5×10^{11}. Since 3888 has the largest excitation cross-section of the He lines and lies fairly low, it is the first to be enhanced as temperature and density increase. Thus it is the only He line enhanced in this case. In a quiescent prominence on June 27, 1956, I found 3888 to be only one third more intense than H8. In this case the temperature determined from Doppler profiles was only around 10,000 degrees.

I should like to express my thanks to Mr. Richard T. Hansen for obtaining the flare spectra at Climax, to Dr. John W. Evans of the Sacramento Peak Observatory for making available prints of the Sacramento Peak Observatory films, and to Dr. R. G. Athay for many discussions on this problem.

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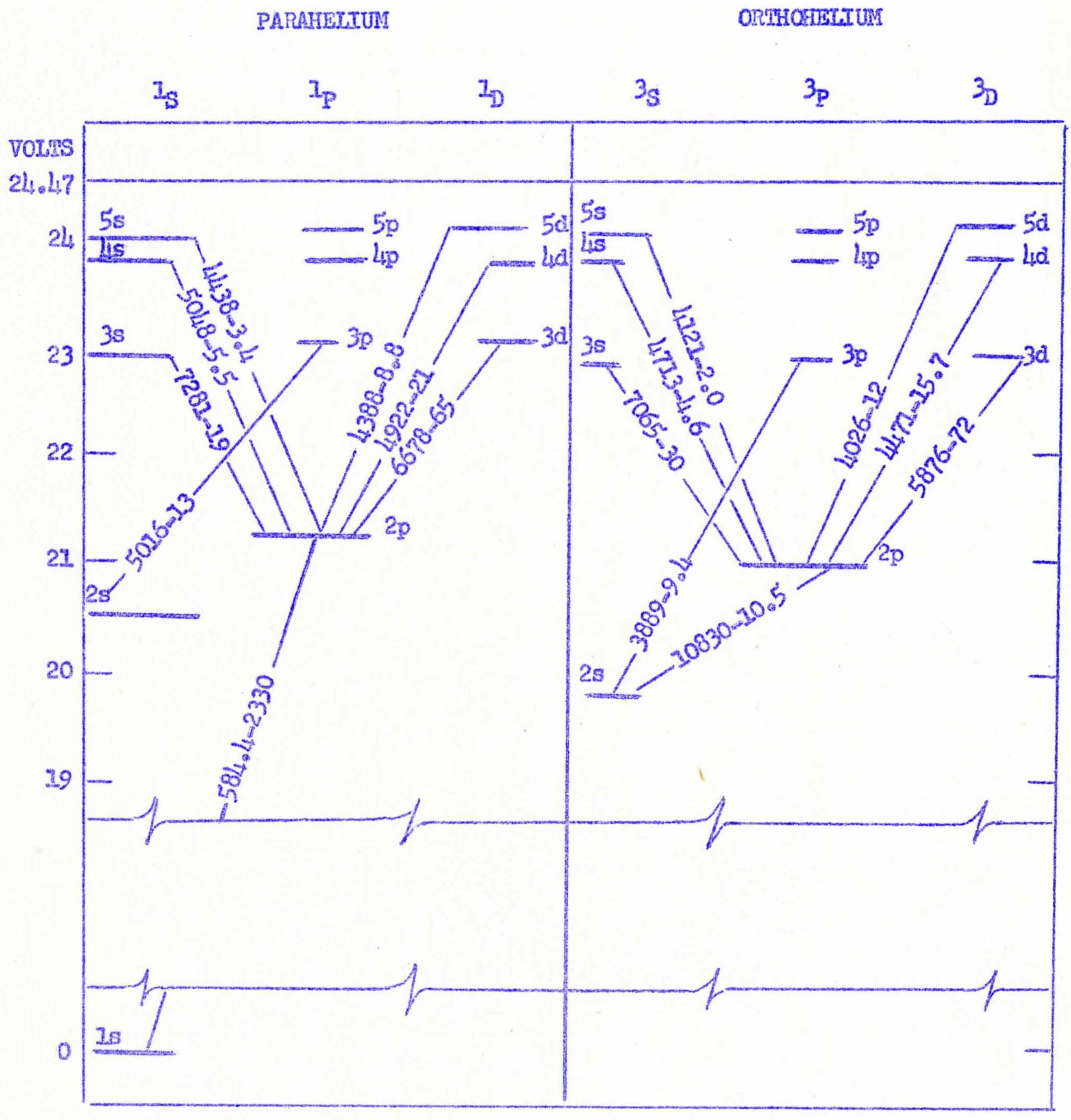

Fig 3. Term Level Diagram for Neutral Helium
Wave Lengths in Å - Transition Probabilities in 10^6 sec^{-1}