

I-4-8. Time Correlation of Auroral Spectra

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Simultaneity and causality between spectral lines of aurorae such as $\lambda 5577$, $\lambda 6300$, H_{α} , N.G. and 1.P.G. were examined. Correlation of 1.P.G. and $\lambda 5577$ is very high, and N.G. also appears with these lines. On ordinary days ($K_p \leq 5$), H_{α} line due to incident proton comes first and a few hours later 1.P.G. can be seen. The height of emitting layer of H_{α} is considered about 300 km, while the one of 1.P.G. is about 80~90 km. Thus it seems that emission of lower layer of 80~90 km high needs some energy accumulation in the upper layer of 100~300 km high. After the establishment of these accumulation about midnight, H_{α} and 1.P.G. seem to appear at the same time. On stormy days ($K_p \geq 6$), H_{α} and 1.P.G. may occur at the same time all over the night. In this case energy accumulation may have been established by the world wide ring current or otherwise by the strong auroral illumination of visible and ultraviolet or X-ray burst.

§1. Introduction

This is the results of our work at the Japanese Antarctic station, Syowa (geographic coordinates: 69°00'S, 39°35'E, 14m from sea level; geomagnetic coordinates: -69.°7, 77.°6) in 1959. The spectrograph was a Meinel patrol type and was set along geomagnetic meridian (11.5° west from geographic north). Its dispersion was about 300 A/mm and resolving power was about 9 A. The relative line intensity was reduced from micropho-

tometric readings with the aid of step wedge. Absolute intensities of lines coming from various altitudes were decided by comparing with the zenith intensity of $\lambda 5577$, whose absolute values were observed by the scanning photometer every one minute.

In auroral spectra, it may be seen several atomic lines of oxygen, hydrogen, sodium and so on and the bands due to N_2^+ and N_2 as shown in Table I. Of these lines, the band series of (0, 0), (0, 1) and (0, 2) of negative group come into view and also fade away at the same time. The 2.P.G. usually appears with the 1.P.G. From these considerations, it is sufficient to select five lines of the 1.P.G., H_{α} , $\lambda 6300$, $\lambda 5577$ and N.G. to examine the main feature of the simultaneity or the causality of auroral spectra.

Table I. Spectral features in the aurorae

Wave Length	Emitter	System [Transition]	
6861	N_2	1.P.G. (3,0) (10,8)	1.P.G.
6768	N_2	1.P.G. (4,1) (11,9)	
6682	N_2	1.P.G. (5,2) (12,10)	
6605	N_2	1.P.G. (6,3) (13,11)	H_{α}
6563	[HI]	H_{α} [3s-2s]	
6526	N_2	1.P.G. (7,4) (14,12)	6300
6454	N_2	1.P.G. (8,5)	
6363	[OI]	red line [$^1D-^3P_1$]	5577
6300	[OI]	red line [$^1D-^3P_2$]	
5892	[NaI]	D [3p-3s]	N.G.
5577	[OI]	green line [$^1S-^1D$]	
5200	[NI]	[$^2D^0-^4S^0$]	N.G.
4861	[HI]	H_{β} [4s-2s]	
4709	N_2^+	N.G. (0,2)	N.G.
4278	N_2^+	N.G. (0,1)	
4059	N_2	2.P.G. (0,3) (1,4) (2,5)	N.G.
3915	N_2^+	N.G. (0,0)	
3805	N_2	2.P.G. (0,2) (1,3) (2,4)	
3578	N_2	2.P.G. (0,1) (1,2) (2,3)	

§2. Simultaneity

As a measure of simultaneity, we used the quantity p_{ij} which is defined as follows:

$$p_{ij} = 1 - \sqrt{\frac{(A_i - C_{ij})(A_j - C_{ij})}{A_i A_j}}$$

where A_i is the number of cases that peaks of i line appeared; C_{ij} is the number of cases both the peaks of i and j lines appeared simultaneously. So p_{ij} represents a kind of probability of simultaneity. In Table II, column 2, it is shown the relative frequency of appearance of the peak number of each line ($A_i / \sum A_i$). In column 3 it is shown percentage value of B_i / A_i where B_i is the

Table II. Simultaneity of auroral spectra. The data used in this table are obtained at Syowa Station in March 1959 through September 1959.

1) On Ordinary Days ($K_p \leq 5$): Total number of peaks = 362

Lines	Appearance frequency of the peaks (%)	Independently appeared probability (%)	p_{ij} (%)				
			5577	N.G.	H_α	6300	1.P.G.
5577	31.8	19.1	—	30.4	13.9	15.5	74.2
N.G.	29.9	55.1	30.4	—	10.7	13.3	17.7
H_α	13.0	51.1	13.9	10.7	—	11.3	14.8
6300	8.0	44.8	15.5	13.3	11.3	—	7.8
1.P.G.	17.4	4.8	74.2	17.7	14.8	7.8	—

2) On Stormy Days ($K_p \geq 6$): Total number of peaks = 609

Lines	Appearance frequency of the peaks (%)	Independently appeared probability (%)	p_{ij} (%)				
			5577	N.G.	H_α	6300	1.P.G.
5577	33.6	24.7	—	39.5	33.2	33.1	74.2
N.G.	18.4	21.4	39.5	—	25.4	23.9	37.4
H_α	16.3	23.2	33.2	25.4	—	30.1	22.6
6300	13.0	24.1	33.1	23.9	30.1	—	17.2
1.P.G.	18.9	0.9	74.2	37.4	22.6	17.2	—

3) In Twilight: Total number of peaks = 215

Lines	Appearance frequency of the peaks (%)	Independently appeared probability (%)	p_{ij} (%)				
			5577	N.G.	H_α	6300	1.P.G.
5577	16.6	0.0	—	49.7	33.5	54.6	39.7
N.G.	36.8	8.8	49.7	—	30.8	78.2	30.3
H_α	3.7	0.0	33.5	30.8	—	66.2	9.7
6300	35.9	9.1	54.6	78.2	66.2	—	16.7
1.P.G.	7.0	6.7	39.7	30.3	9.7	16.7	—

number of peaks i appeared independently without accompanying peaks of other line. In column 4~8 the percentage values of p_{ij} are shown.

Ordinary days do not mean magnetic quiet days but the days on which the planetary K -index K_p is smaller than five. On these days, positive bay and negative bay disturbances are usually observed. From this table it may be said that the N.G. and H_α are likely to occur independently, and most of the 1.P.G. appear with $\lambda 5577$.

On stormy days, that is the days on which K_p is greater than 6, we can see the close correlation between the 1.P.G., N.G. and $\lambda 5577$, and $\lambda 6300$ is enhanced. Simultaneity between H_α and other line is high compared with ordinary days.

In twilight the red line of oxygen is very

likely to appear, and the other line such as $\lambda 5577$, N.G. and H_α are accompanied by the red line.

Fig. 1 shows the spacial simultaneity of the red line of oxygen, the red line is frequently appeared at evening. On stormy days the red line is also enhanced at dawn. On the contrary, H_α is usually observed comparatively localized as shown in Fig. 2. These circumstances are also held in individual cases. Statistically H_α line seems to have almost no local time dependence, nor significant difference between stormy and ordinary days.

The 1.P.G. is strongly localized as shown in Fig. 3, and in this case the appearance frequency is large after local midnight. 1.P.G. appears much more frequently on stormy days than on ordinary days.

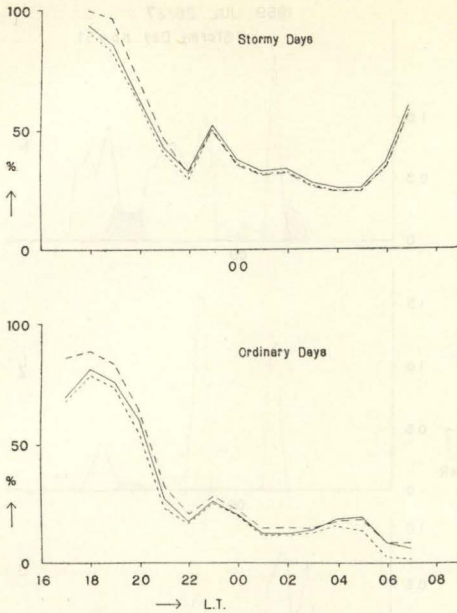


Fig. 1. Appearance frequency of $\lambda 6300$. Dotted line corresponds to zenith angle of 75 degrees in the north, full line corresponds to zenith and broken line to 75 degrees in the south.

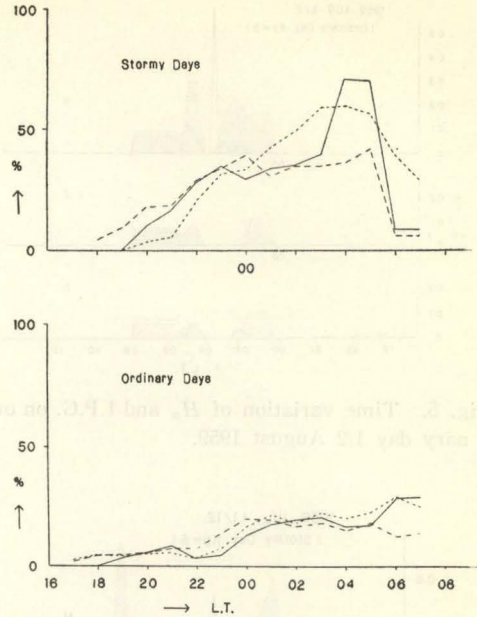


Fig. 3. Appearance frequency of 1.P.G.

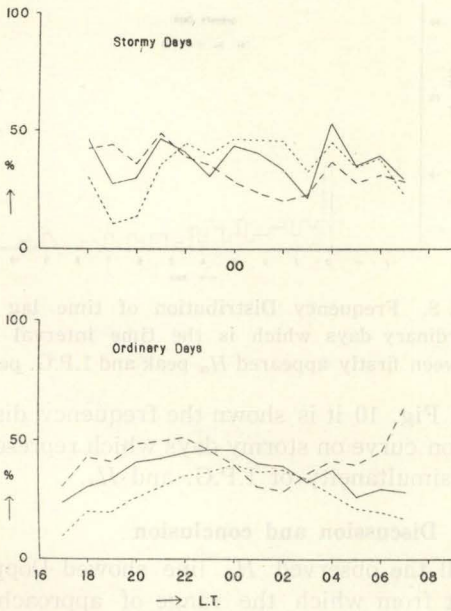


Fig. 2. Appearance frequency of H_{α} .

§ 3. Causality

Next, we like to examine the causality between H_{α} line and the other line. One example is shown in Fig. 4. It may be seen that the 1.P.G. appears about one or two

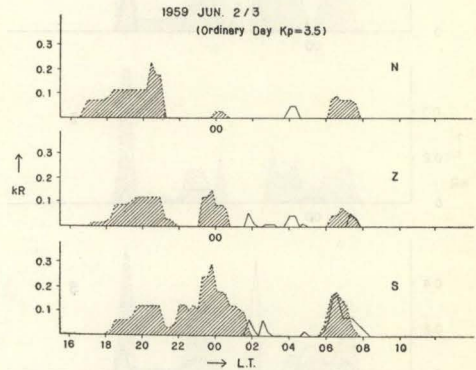


Fig. 4. Time variation of H_{α} and 1.P.G. in kilorayleighs (kR). Dotted line shows the H_{α} line and full line the 1.P.G. N, Z and S have the same meanings as in Fig. 1, that is, N corresponds to zenith angle of 75 degrees in the north, etc. Abscissa is local time which precedes to U.T. by three hours. Geomagnetic midnight almost coincides with 03:00 L.T.

hours later after H_{α} appears. But after midnight, both H_{α} and the 1.P.G. seem to appear at the same time. Fig. 5 also shows similar tendency, that is, at first H_{α} appears and then 1.P.G. follows and after the appearance of the first peak of 1.P.G. both H_{α} and 1.P.G. appear at the same time.

Fig. 6 and Fig. 7 are the similar examples on stormy days. In this case 1.P.G. and H_{α} may appear at the same time all over the

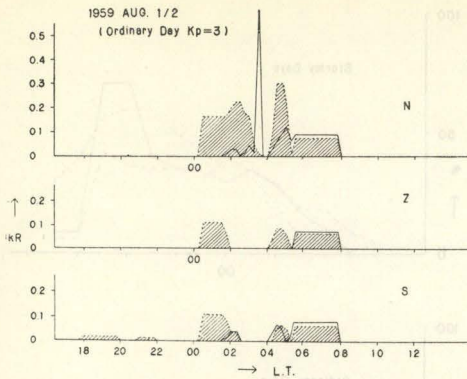


Fig. 5. Time variation of H_{α} and I.P.G. on ordinary day 1/2 August 1959.

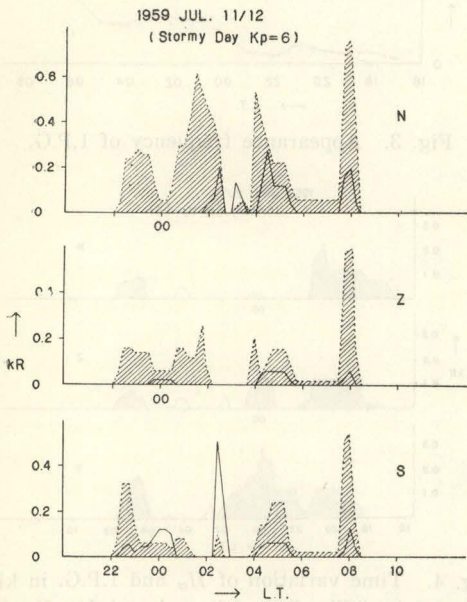


Fig. 6. Time variation of H_{α} and I.P.G. on stormy day 11/12 July 1959.

night. As in the case of Fig. 7, sometimes even I.P.G. precedes H_{α} .

Fig. 8 shows the frequency distribution of time lag from firstly appeared H_{α} to the I.P.G. on ordinary days. In this case, the I.P.G. appears always after H_{α} emission, and its mean time lag is about three hours. On ordinary days, after the first peak of I.P.G., H_{α} and I.P.G. come into view almost at the same time as mentioned above. The frequency distribution of time lag of this case is shown in Fig. 9. In this case the mean time lag is about 12 minutes, that is, both lines appear almost at the same time.

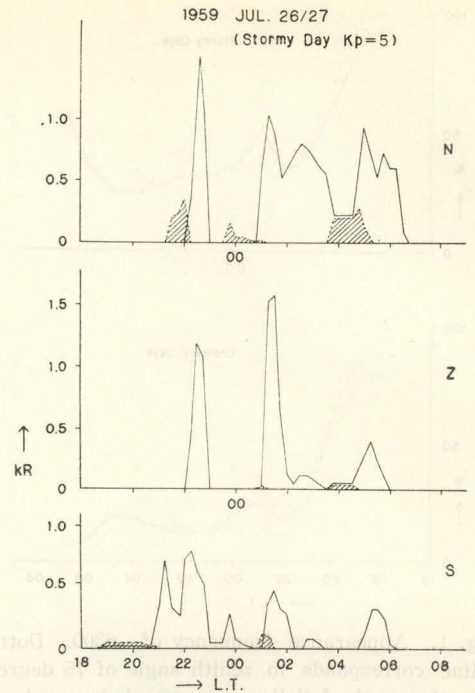


Fig. 7. Time variation of H_{α} and I.P.G. on stormy day 26/27 July 1959.

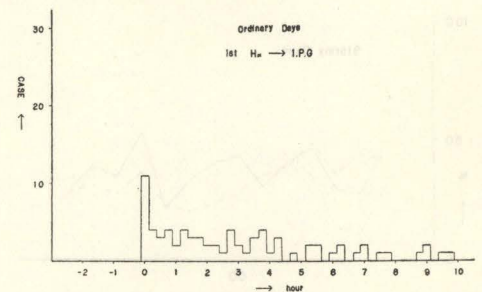


Fig. 8. Frequency Distribution of time lag on ordinary days which is the time interval between firstly appeared H_{α} peak and I.P.G. peak.

In Fig. 10 it is shown the frequency distribution curve on stormy days which represents the simultaneity of I.P.G. and H_{α} .

§ 4. Discussion and conclusion

All the observed H_{α} line showed Doppler shift from which the range of approaching velocity has been calculated as $1 \times 10^7 \sim 2 \times 10^8$ cm/sec. This is considered as the evidence that the cause of H_{α} emission is due to incident protons from the sun. The height of emission layer of H_{α} is 300 km or more¹⁾. The observed facts taken with the Geiger counter in the rocket flight into the aurora

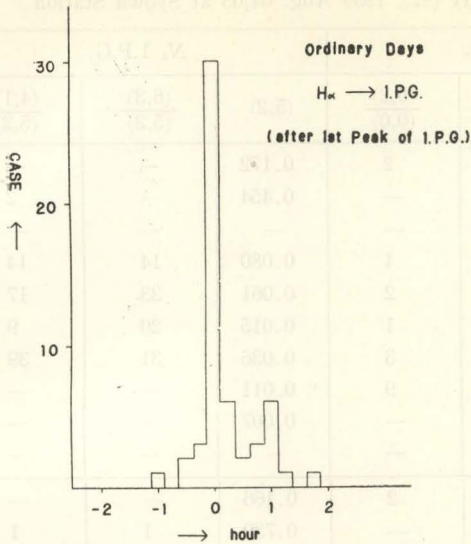


Fig. 9. Frequency distribution of time lag on ordinary days which is the time interval between H_{α} peak after the first peak of I.P.G. and the next coming I.P.G. peak.

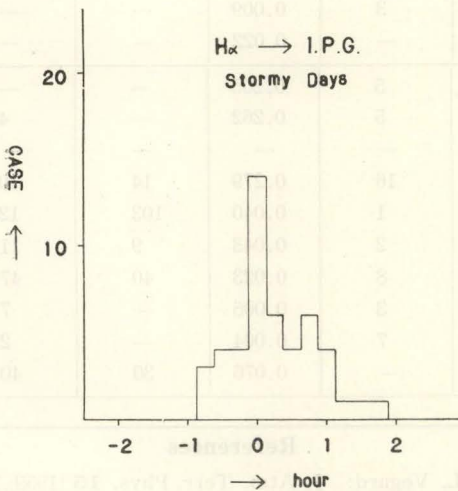


Fig. 10. Frequency distribution of time lag on stormy days which is the time interval between H_{α} and I.P.G. peaks.

are as follows; the proton flux is not large in the aurora, while at the luminous centre a remarkable monoenergetic electron beam of about 6 keV can be seen^{2), 3)}.

The height of the emission layer of the I.P.G. measured by our photographic triangulation in May 1959 was between eighty and ninety kilometers. Advanced station

had been located at Skjegget (69°26'S, 39°35.5'E and 14 m above sea level).

From these facts, it will be suggested that the incident proton comes down to about 300 km high capturing electron and emits H_{α} and H_{β} lines; but in this stage no incident protons or electrons reach to the E layer⁴⁾. By continuous illumination of the incident protons or electrons, some excess energy may be accumulated in the F_1 and F_2 regions. If this conserved energy exceeds a certain critical value, the monoenergetic electron beam will be formed, or otherwise it leaks into the lower layer through the disturbed magnetic field, and it causes strong emission at the E layer. Once this nonequilibrium state is established, H_{α} and I.P.G. may appear at the same time. On stormy days it may be guessed that some chemical potential has been accumulated in F layer beforehand, because of the continuous strong auroral activity, X-ray radiations⁵⁾ or otherwise the world wide ring bay current in the F layer. And for this reason both lines may appear simultaneously on stormy days.

This energy accumulation also may be seen in the following fact. In Table III it is shown the photometric results of the absolute intensity and the intensity ratio of the band system due to N_2^+ and N_2 . Intensity ratios are considered as a measure of relative vibrational temperature and accordingly of internal energy. In the table the intensity ratio seems to come to maximum some minutes after the time of maximum intensity of the band.

Ionospheric observation by echo sounding was carried out by Mr. Wakai at Syowa station in 1959. Comparing his data with ours, fairly good time correlation was found between H_{α} emission and the appearance of sporadic F layer and also between $\lambda 5577$ and sporadic E layer. These relations also suggest the causality between H_{α} and the I.P.G. or luminous aurorae.

Simultaneity of the red line of oxygen and spread F layer was also found.

To elucidate the mechanism of excitation of aurorae, these simultaneity and causality must be considered with more knowledge of cross section and transition probability of some radicals.

Table III. Band intensity (kR) and relative intensity (%). 1959 Aug. 04/05 at Syowa Station

	L.T.		N_2^+ N.G.			N_2 I.P.G.		
	from	to	(0,0)	$\frac{(0,1)}{(0,0)}$	$\frac{(0,2)}{(0,0)}$	(5,2)	$\frac{(6,3)}{(5,2)}$	$\frac{(4,1)}{(5,2)}$
N 75°	18:33	20:54	0.234	43	2	0.172	—	—
	20:54	22:47	0.061	33	—	0.454	—	2
	—	—	—	—	—	—	—	—
	00:23	00:51	1.460	36	4	0.080	14	14
	00:51	01:15	3.410	26	2	0.061	33	17
	01:15	01:42	3.710	23	1	0.015	20	9
	01:42	03:33	3.840	27	3	0.036	31	39
	03:33	05:21	0.157	20	9	0.011	—	—
	05:21	07:12	0.099	—	—	0.007	—	—
07:12	07:41	—	—	—	—	—	—	
Z	18:33	20:54	0.186	42	2	0.166	—	—
	20:54	22:47	0.039	27	—	0.730	1	1
	—	—	—	—	—	—	—	—
	00:23	00:51	0.963	31	21	0.058	18	18
	00:51	01:15	7.400	15	1	0.042	25	19
	01:15	01:42	1.550	22	2	0.045	12	9
	01:42	03:33	10.100	20	1	0.024	30	39
	03:33	05:21	0.140	22	2	0.008	—	—
	05:21	07:12	0.146	19	3	0.009	—	—
07:12	07:41	0.065	—	—	0.022	—	—	
S 75°	18:33	20:54	0.312	40	5	0.205	—	—
	20:54	22:47	0.213	34	5	0.262	—	4
	—	—	—	—	—	—	—	—
	00:23	00:51	0.721	24	16	0.279	14	10
	00:51	01:15	8.400	15	1	0.040	103	12
	01:15	01:42	1.900	27	2	0.043	9	11
	01:42	03:33	1.650	61	8	0.023	40	47
	03:33	05:21	0.393	30	3	0.006	—	7
	05:21	07:12	0.102	5	7	0.004	—	2
07:12	07:41	0.296	46	—	0.076	30	40	

Acknowledgement

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Discussion

Tohmatsu, T.: Dr. Harang suggested yesterday that H_α luminosity spreads almost all over the sky, while bright aurora is confined in small part of the sky. Don't you

think this is the reason why H_{α} intensity shows rather flat occurrence frequency distribution?

Nakamura, J.: H_{α} luminosity spreads out to wider region, but its nocturnal variation shows rather rapid change. It is because of the statistical operation through many nights that almost no local time dependence can be seen in Fig. 2.

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1-4-9. Low Latitude Red Aurora and Low Energy Protons in Van Allen Belt

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It is proved that the great intensity ratio of the red to the green line of O-atom accompanied by the strong emission of N_2^+ N.G. is a useful criterion to distinguish the aurora excited by a few keV protons from those of other origins. The red line enhancement is due to the low temperature of the electrons ejected by proton bombardment. The estimated temperature and the red-green ratio is 0.5, 1, 2.5 and 4 eV and 500, 45, 12 and 6.5 for protons of 1, 2, 5 and 25 keV respectively. The efficiency of the red line excitation by the secondary electrons of 3 keV protons is estimated to be about one photon per one electron. If we take as a model of low latitude aurora the following: thickness 100 km, the red line brightness 10 kR at 250 km height and 1 kR at 600 km, and the red-green ratio 20, then the energy of the incident proton must be about 3 keV, and the necessary flux is $8 \times 10^8/cm^2, sec$ at 250 km and $3 \times 10^{10}/cm^2, sec$ at 600 km. This large increase of flux with height and many other evidences indicate that they come from Van Allen Belt.

Direct detection of auroral protons has not been done yet, as their energy is too low to be detected by the usual instruments born on rockets. We can get knowledge about them only through the analysis of their behaviors in auroral displays. Therefore we will try here to make clear what are the characteristics of the spectra excited by the protons, and try to answer what type auroras are due to protons of what energy. Estimation of proton flux from the spectral intensity will also be given. Particular attention will be paid to a few keV protons because they are surely the main component of the auroral protons.

great enhancement of the red oxygen line. This is a consequence of the smallness of the energy of the secondary electrons ejected by the proton bombardment. Let an electron of mass m be initially free and at rest, and collide with a proton of mass M and energy E , then the maximum energy ϵ_m got by the electron is

$$\epsilon_m = 4Em/M. \quad (1)$$

This formula can be applied to bound electrons provided the proton energy is high enough. Bates⁽¹⁾ and his collaborators have calculated the energy spectra of the secondary electrons ejected from H and Ne by proton bombardment. Fig. 1 shows their results. The dotted parts of the curves are our extrapolation. Eq. (1) has given very powerful aid for the purpose. We believe the ambiguity inherent to the extrapolation

§1. Red-green ratio

The most remarkable feature of the spectra excited by the protons of a few keV is the