10. SPECTRAL STUDIES OF METEORS AT THE TOKYO ASTRONOMICAL OBSERVATORY

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1. Introduction

Our program of meteor research has been changed since November, 1963, by introducing spectral photography at the Dodaira branch station of the Tokyo Astronomical Observatory, in addition to the direct photography at the Mitaka Station. Observations at these two stations are basic, and they have been supplemented in case of need by observations at the temporary station at Tatebayashi, situated about 40 km Northeast of Dodaira. Double- or triple-station observations were carried out mainly during the active period of the major streams, such as Quadrantids, Perseids, Leonids or Geminids, with the purpose of the dynamical and physical studies of meteors. The coordinates of these three stations are as given in Table 1.

Table 1

Coordinates of stations

	Longitude	Latitude	Height
Dodaira	139°11′37″	36°00′10″	876^m
Mitaka	139°32′30″	35°40′11″	60^m
Tatebayashi	139°30′05″	36°15′27″	22^m

This report contains the outline of the program with a short description of the instruments used and the partial results concerning the spectrograms obtained up to the present.

2. The Equipment and Research Procedure

The direct purpose of our observation program is to take good meteor spectrograms supported by photographic double- or triple-station data. We employed three types of cameras for this purpose, i.e. fixed spectro-cameras, equatorially mounted direct cameras, and small fixed wide-angle cameras for the timing of the meteors' apparitions.

All the spectro-cameras are installed at Dodaira. They have prisms or transmission gratings of various dispersion values, 1500 Å/mm – 170 Å/mm, in front of the camera

Kresák and Millman (eds.), Physics and Dynamics of Meteors, 105–118. © *I.A.U.*

lenses. Direct photography cameras are equatorially mounted automatic ones specially designed by us and are installed at Dodaira and Mitaka (Figure 1). Each camera consists of four camera lenses arranged so as to photograph the adjoining sky fields, $60° \times 80°$ in total, on two rolls of film of aerial photography instead of photographic plates. This will evidently weaken the conservation of position on the photograph

FIG. 1. *Automatic Meteor Camera 'A' (Dodaira Station).*

but, according to our experience, our film-backing device, with the use of vacuum suction, has proved to be satisfactory. Roll-film is far more convenient than photographic plates for converting cameras into automatic loading ones. Moreover, we think that the collection of more data in an efficient way is far more important than to secure relatively more precise spectrograms, or direct photographs, with the use of photographic plates. The ease in obtaining high-sensitive and suitable photographic emulsions in the form of film was also a reason why we had to change our policy on meteor photography and spectroscopy.

The camera can be operated (partially programmed) under a remote-control system. The camera setting and the selection of the exposure duration can be performed or programmed at the control panel, and the film is automatically shifted by one frame during the movement of the camera for the next setting, after the completion of the desired length of the exposure. The times of the beginning and ending of the exposure are photographically recorded on the same meteor film. The rotating shutter is operated by an accurate oscillator.

Up to the present, these automatic cameras have been used almost exclusively for direct photography, but we plan to convert them into grating cameras, as the zero-order image of such a camera is as satisfactory as direct photography, allowing for the loss of light intensity.

General data about our cameras are summarized in Table 2.

Table 2

Instrumental data

Designation	Aperture	Focal length	Field area	Type of Dispersion System	Dispersion[b]
	Fixed Spectrocamera (at Dodaira)				
NT	11 cm	50 cm	22° × 18°	Prism BK7 22°	450 Å/mm
G	7	30	35 × 29	Prism F3 26	260
K-20	5·7	20	39 × 30	Prism BK7 46	385
NA	5·7	20	35 × 27	Grating 150 grv/mm[a]	320
NB	5·7	20	35 × 27	Grating 150	320
NC	5·7	20	35 × 27	Grating 300 grv/mm	170
ND	5·7	20	35 × 27	Grating 300	170
	Four-lens Photo Camera				
A	5·7	20	60 × 80	(at Dodaira)	
B	5·7	20	60 × 80	(at Mitaka)	
	Timing Camera			(at Dodaira)	
t	1·5	5	45 × 45		
	Six cameras of the same type are used.				

[a] Blazed for maximum intensity near 6000 Å in the first order on one side.
[b] Mean value, $H\gamma \sim H\delta$.

3. Observations, Analysis and Results in General

We have made observations on 80 nights, about 350 hours in total. The number of meteor spectra secured throughout the period amounts to 79, as given in Table 3. About one-half of these spectra were obtained during the active period of the Leonids in 1965, and the rest consist of the Leonids of 1963 and 1964, Perseids, Taurids, Geminids, and sporadics. Some specimens of our meteor spectra are reproduced here as Figures 2–4.

The bright meteor shown as Figure 3 (spectrum No. 50) appeared on the night of November 16, 1965. This was brighter than the full moon and left its train for over 10 min. The train was also photographed by many amateur observers in Japan.

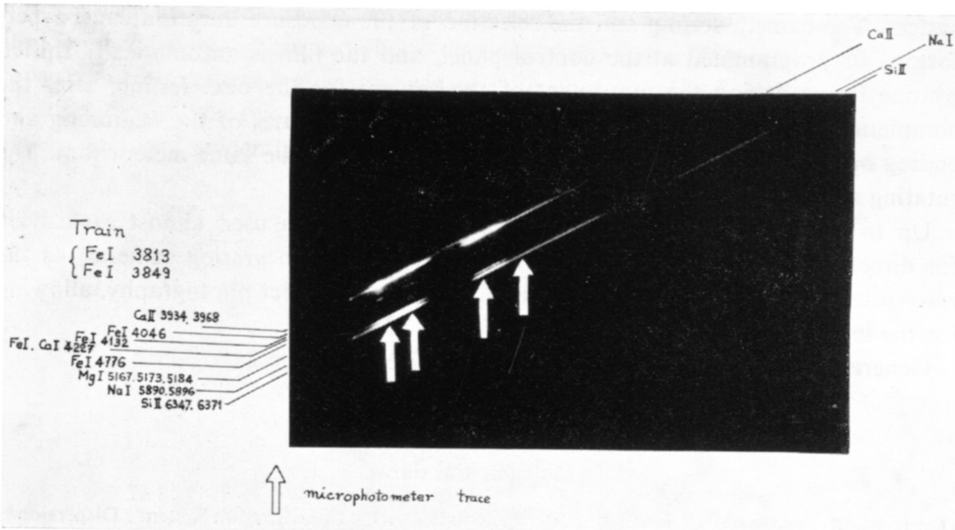

FIG. 2. *Prismatic spectrum No. 11 (Aug. 12, 1964). Photometric tracings are indicated by arrows.*

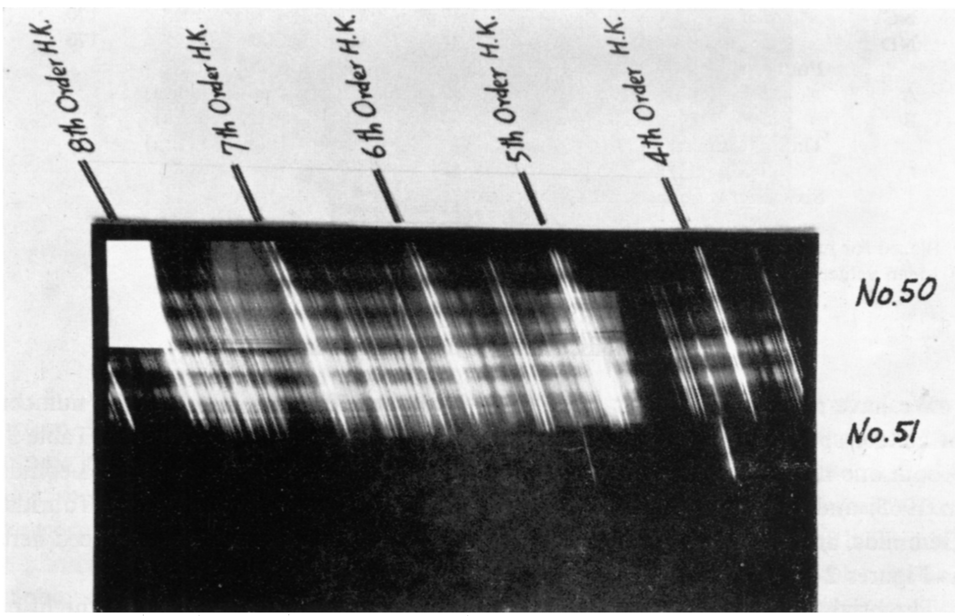

FIG. 3. *Higher-order grating spectra of a bright meteor, No. 50 (Nov. 16, 1965). A faint spectrum of another meteor, No. 51, is also recorded in the same frame.*

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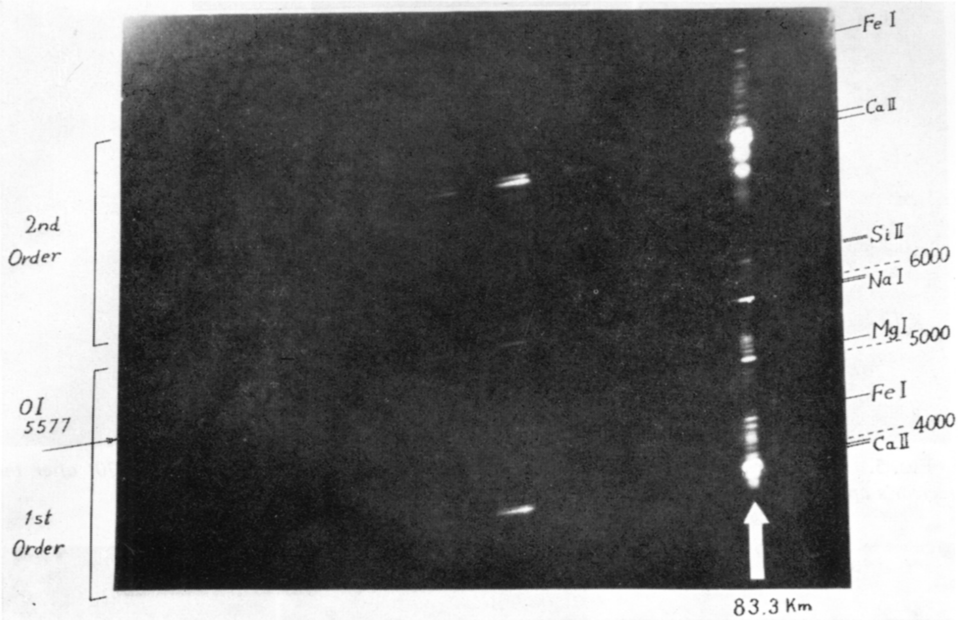

FIG. 4. *Grating spectrum No. 59 of a flaring meteor (Nov. 16, 1965). The height of the flare (arrow) is 83·3 km.*

Table 3

Statistics of our spectra

Stream	Number of Lines				Total
	⩾50	49–20	19–10	9–1	
Perseids	–	–	2	12	14
Taurids	–	–	–	2	2
Leonids	6	1	6	25	38
Geminids	–	3	1	11	15
Sporadics	–	–	–	10	10
Total	6	4	9	60	79

Photographs, such as Figures 5 and 6, have been analysed by Mr. Keiji Saito of our Observatory. His detailed discussion will be published by him elsewhere in the near future. However, we quote here his partial result on the variation of the wind's direction and velocity as a function of height. Mr. Saito drew a hodographic figure concerning this problem, reproduced here as Figure 7. Fourth- to eighth-order grating spectra of this meteor have also been secured at Dodaira by us, but the analysis has not yet been completed.

Our usual process of analysis of a good spectrogram is as follows:

(a) The identification of the observed emission lines

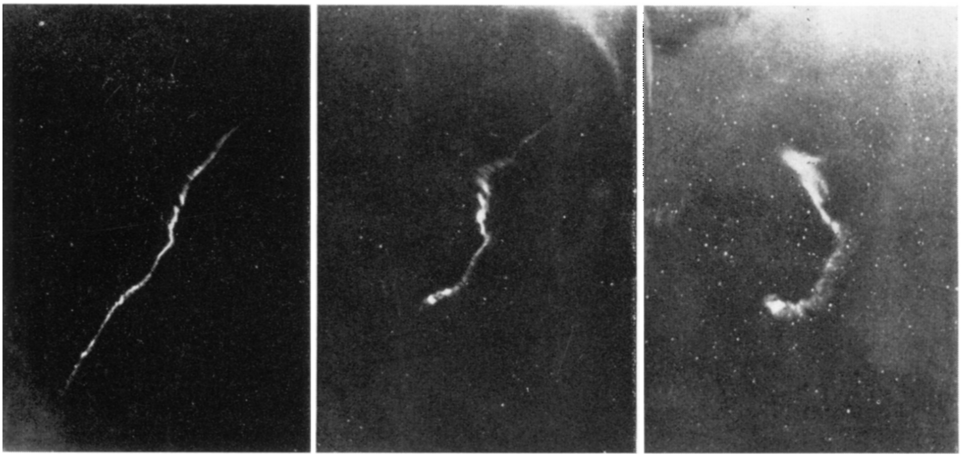

FIG. 5. *Variation of the train of a bright meteor photographed about 30ˢ, 50ˢ and 70ˢ after the meteor's apparition (left to right). (Photograph by Mr. Y. Hirano of Ashikaga.)*

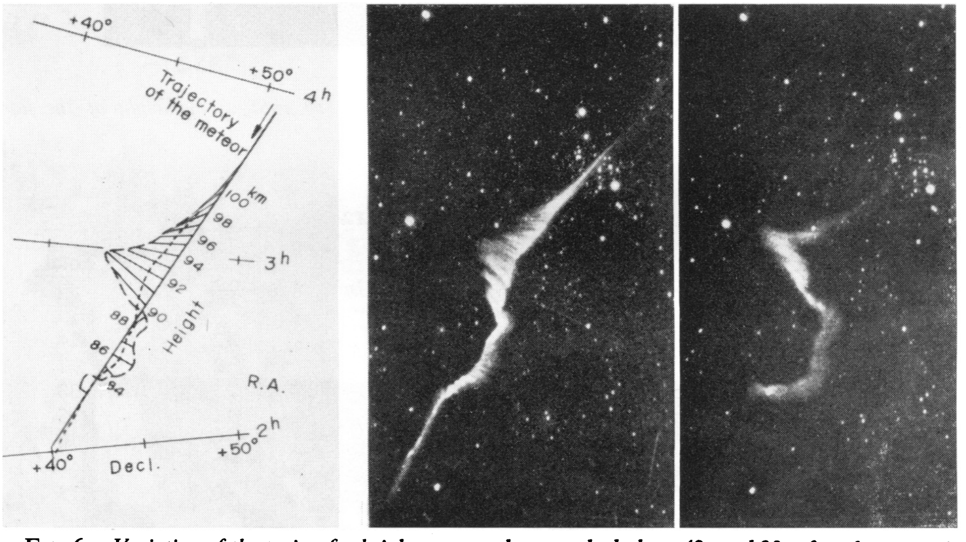

FIG. 6. *Variation of the train of a bright meteor photographed about 48ˢ and 92ˢ after the meteor's apparition (middle to right). The left diagram shows two photographs in one. Height, right ascension and declination are also indicated. (Photograph by Mr. K. Asoya of Utsunomiya.)*

(b) The photometric analysis to determine the energy distribution of the meteor radiation with wavelength;

(c) The attempt for the determination of the temperature and chemical composition, as related to the radiation, assuming local thermal equilibrium;

(d) The determination of the local and heliocentric orbit and velocity of the

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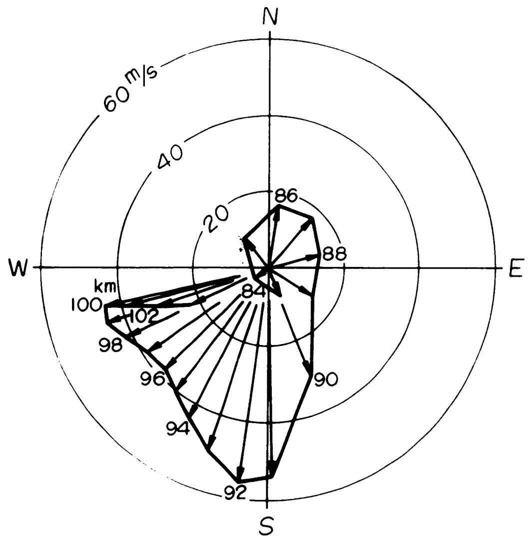

FIG. 7. *Hodograph of the wind-velocity vector. The direction of the wind, together with its velocity, is shown as a function of height.*

meteor concerned, based on the double- or triple-station photographic observations, to investigate the relations between the radiation and the meteor's height.

Through the analysis of selected spectrograms, as given above, the following general results have been obtained from our meteor spectra:

(a) On the spectrograms of the fast meteors, such as Leonids and Perseids, Ca II H and K lines are generally the strongest. But, after carrying out the correction for the spectral sensitivity, Si II lines at 6347 Å and 6371 Å seem to become stronger than the others. In general, these two silicon lines do not appear so strong because they are located in a region of quite low sensitivity for the normal panchromatic emulsion. To confirm the fact, we are now planning to take meteor spectrograms with the use of an infrared film.

(b) Other lines appearing on the spectrograms of the fast meteors are those of Na I, Mg I and Fe I. In the case of the very bright meteor, the lines of Co I, Cr I, Ni I and the forbidden line of O I (5577 Å) are observed.

(c) In the case of the slow meteors, such as Geminids, nearly all the lines are identified with Fe I except for the D lines of Na I.

(d) Though the variation of line intensities, increase or decrease, generally takes place nearly simultaneously for every spectral line, the rate of the variation is not always equal. Only the forbidden line of O I (5577 Å) shows quite peculiar aspects, appearing long before the other lines, i.e. at the great height of over 100 km, and disappearing first.

(e) From the previous results of our analysis, we do not think a reliable temperature of the meteor was obtained. As for the chemical composition, it seems that silicon is the most abundant element in fast meteors.

(f) We cannot yet decide if the differences in the spectra of the fast and the slow meteors respectively are due to the velocity difference between these two groups or to their original compositions.

(g) It might be worth while to note that the heights of the points where a meteor flared and darkened seemed to coincide with the layers where the wind was of zero velocity. This fact should be carefully studied with the use of more material.

4. On the Spectrum of a Leonid Meteor

During our Leonid observation period, a fairly bright meteor appeared at 18^h21^m UT, November 16, 1965, in the Southwest sky at Dodaira station. The magnitude was estimated as about −5. Fortunately, we secured a grating spectrogram (spectrum No. 56) with the fixed camera NB. The quality of the spectrogram was good enough to carry out further analysis. This is shown as Figure 8. On this spectrogram one can easily see the forbidden line of O I (5577 Å) at the left side. Table 4 gives observational data for spectrum No. 56.

Neither cameras at Mitaka nor those at Tatebayashi could record the meteor's

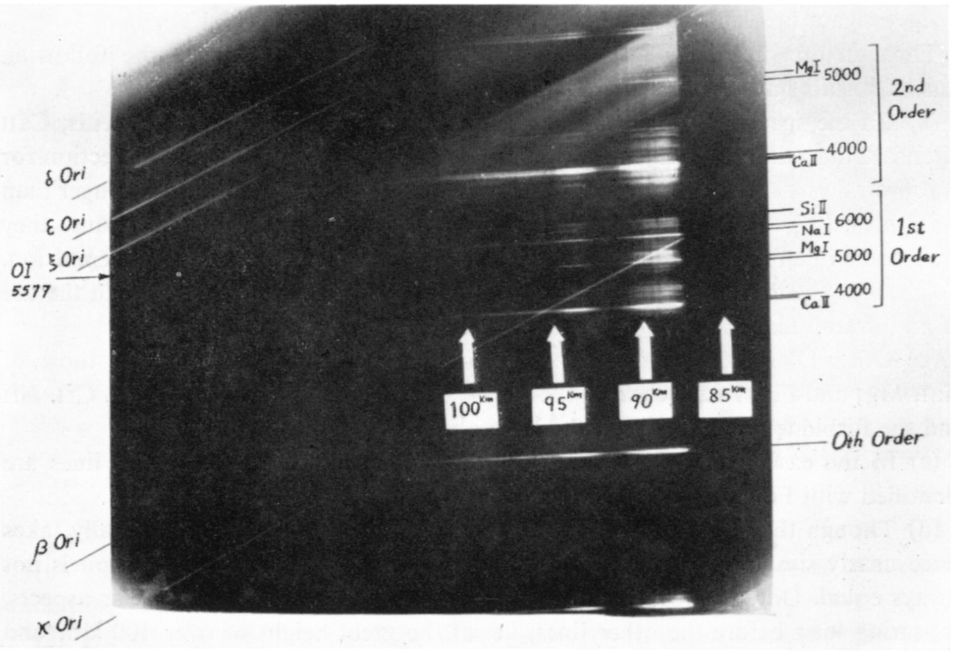

FIG. 8. *Spectrum No. 56 (Nov. 16, 1965, 18^h21^m UT). Heights of various points are indicated by arrows.*

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Table 4

Observational data of Spectrum No. 56

Station: Dodaira
Exposure: 1965 Nov. 16, $18^h20^m15^s - 18^h47^m15^s$ (UT)
Angle between the meteor's path and the direction of the dispersion: 87°
Appearance: R.A. $5^h50^m.5$ Decl. − 7°18′ (1950·0)
Disappearance: R.A. $4^h51^m.5$ Decl. − 13° 6′ (1950·0)
Brightest Point { R.A. $4^h58^m.0$ Decl. − 12°22′ (1950·0)
Azimuth from South: 41°35′, Altitude 31°8′
Photographic Film: Tri-X (ASA400), 10 × 12·5 cm, pack film
Dispersion: 320 Å/mm (Grating)

photographic path because of its low altitude, but we happened to know that Messrs. Y. Kashiwagi and Y. Asai photographed the same meteor at Odawara, about 90 km to the South of Dodaira. Through their kind offer of the film, we could fortunately determine the meteor's aerial path as given in Table 5.

Table 5

Aerial path of the meteor (Spectrum No. 56)

Ref. No. of Measured Point	Apparent Path at Dodaira (1950·0) α	δ	Meteor's Coordinates Longitude	Latitude	Height
1	$5^h40^m.5$	− 7°18′	138°24′E	35°1′N	116·68 km
2	5 30·4	− 8°34′	138°20′	35°1′	109·63
3	5 14·3	− 10°30′	138°15′	35°2′	99·11
4	5 6·3	− 11°25′	138°12′	35°2′	94·07
5	5 4·4	− 11°39′	138°12′	35°2′	92·87
6	5 1·4	− 11°59′	138°11′	35°2′	91·06
7	4 58·0	− 12°22′	138°10′	35°2′	88·95
8	4 51·5	− 13° 6′	138° 7′	35°2′	84·94

As seen from Table 5, the meteor was photographed between the heights of 117 km and 85 km, giving rise to bright flares three times. The brightest position was at the height of 89 km.

The identification of spectral lines, 73 in all, has been made with care, and the results are summarized in Table 6. In this table the number in the bracket standing at the right side of each row of the last column is the multiplet number given in Moore's multiplet table. In Table 7 the approximate value of each line's relative intensity is given. The values are arranged according to the serial reference number corresponding to those used in Table 6. The measured values correspond to the meteor's brightest position at a height of 89 km. Over all, in addition to the forbidden line of O I, the lines of eight elements, Ca, Si, Mg, Na, Fe, Co, Ni and Cr, are found in

Table 6

Identification of lines (Spectrum No. 56)

Measured Wavelength				Wavelength of Multiplet Table					
1st order		2nd order							
		40	3710·61	Fe I	3709·246	(21)			
					3719·935	(5)			
					3722·564	(5)			
		41	3724·68	Fe I	3734·867	(21)			
					3737·133	(5)			
1	3743·37	42	3740·38	Fe I	3745·561	(5)			
					3745·901	(5)			
					3748·264	(5)			
					3749·487	(21)			
		43	3750·00	Fe I	3758·235	(21)			
		44	3822·02	Fe I	3820·428	(20)			
					3824·444	(4)			
					3825·884	(20)			
		45	3859·17	Fe I	3849·969	(20)			
					3859·913	(4)			
					3865·526	(20)			
2	3933·67	46	3933·67	Ca II	3933·664	(1)			
3	3972·23	47	3969·17	Ca II	3968·470	(1)			
		48	4002·22	Fe I	4005·246	(43)			
				Co I	3995·306	(31)			
4	4037·15	49	4035·13	Fe I	4045·815	(43)			
				Co I	4045·386	(31)			
5	4065·67	50	4065·50	Fe I	4063·597	(43)			
					4071·740	(43)			
6	4131·44	51	4133·97	Si II	4130·884	(3)			
					4128·053	(3)			
				Fe I	4132·060	(43)			
		52	4196·83	Fe I	4202·031	(42)			
7	4217·88	53	4223·17	Ca I	4226·782	(2)			
				Fe I	4227·434	(693)			
		54	4248·39	Fe I	4250·790	(42)			
				Cr I	4254·346	(1)			
8	4264·92	55	4268·04	Fe I	4271·764	(42)			
				Cr I	4274·803	(1)			
		56	4288·64	Fe I	4294·128	(41)			
				Cr I	4289·721	(1)			
		57	4304·23	Fe I	4307·906	(42)			
9	4317·15	58	4321·32	Fe I	4325·765	(42)			
		59	4346·93	Fe I	4337·049	(41)			
10	4375·19	60	4375·13	Fe I	4383·547	(41)			
		61	4401·15	Fe I	4404·752	(41)			
				Ni I	4401·547	(86)			
11	4419·44	62	4423·48	Ca I	4425·441	(4)			
				Fe I	4422·570	(350)			
		63	4455·75	Ca I	4455·887	(4)	Fe I	4454·383	(350)
					4454·781	(4)			
12	4476·10	64	4477·78	Fe I	4466·554	(350)			
					4476·021	(350)			
13	4524·77	65	4523·90	Co I	4530·949	(150)			
					4533·985	(150)			

Table 6 (Continued)

Measured Wavelength				Wavelength of Multiplet Table		
1st order		2nd order				
		66	4553·78	Co I	4549·658	(150)
14	4564·72	67	4567·01	Co I	4565·578	(150)
15	4636·07			Co I	4629·359	(156)
16	4698·95			Co I	4693·190	(156)
					4698·389	(156)
17	4777·68			Co I	4768·072	(156)
					4771·108	(156)
18	4913·00			Fe I	4918·999	(318)
					4920·509	(318)
19	4950·35			Fe I	4957·302	(318)
					4957·603	(318)
20	5005·71			Fe I	5006·126	(318)
21	5044·50			Fe I	5049·825	(114)
22	5104·79			Fe I	5110·414	(1)
23	5165·29	68	5163·55	Mg I	5167·322	(2)
					5172·684	(2)
					5183·604	(2)
		69	5179·28	?		
24	5219·68	70	5224·99	Fe I	5226·868	(383)
					5232·946	(383)
25	5266·30	71	5265·04	Fe I	5263·314	(553)
					5266·562	(383)
					5269·541	(15)
26	5321·26	72	5323·21	Fe I	5324·185	(553)
					5328·042	(15)
27	5365·63	73	5365·50	Fe I	5371·493	(15)
28	5386·53			Fe I	5383·628	(553)
30	5448·93			Fe I	5446·920	(15)
					5455·613	(15)
31	5493·63			Fe I	5497·519	(15)
					5501·469	(15)
32	5524·76			Co I	5530·780	(38)
33	5590·46			Co I	5590·744	(90)
34	5673·83			Na I	5682·633	(6)
					5688·205	(6)
35	5888·86			Na I	5888·953	(1)
					5895·923	(1)
36	5972·04			Si II	5957·612	(4)
					5978·970	(4)
				Co I	5991·890	(90)
37	6152·76			Na I	6154·225	(5)
					6160·747	(5)
38	6239·91			Si I	6237·62	(27)
					6243·86	(28)
					6244·56	(27)
					6254·25	(28)
					6273·34	(28)
				Co I	6230·968	(37)
					6282·636	(37)
39	6347·96			Si II	6347·091	(2)
					6371·359	(2)

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Table 6 (Continued)

Measured Wavelength 1st order		2nd order		Element and Multiplet			
		40	3710·61		Fe I (5)	Fe I (21)	
		41	3724·68				
1	3743·37	42	3740·38		↓		
		43	3750·00			↓	
		44	3822·02		Fe I (4)	Fe I (20)	
		45	3859·17		↓	↓	
2	3933·67	46	3933·67	Ca II (1)			
3	3972·23	47	3969·17	↓			
		48	4002·22		Fe I (43)		Co I (31)
4	4037·15	49	4035·13				↓
5	4065·67	50	4065·50				
6	4131·44	51	4133·97	Si II (3)	↓		
		52	4196·83		Fe I (42)		
7	4217·88	53	4223·17	Ca I (2)		Fe I (693)	
		54	4242·39				Cr I (1)
8	4264·92	55	4268·04				
		56	4288·64			Fe I (41)	↓
		57	4304·23				
9	4317·15	58	4321·32		↓		
		59	4346·93				
10	4375·19	60	4375·13				
		61	4401·15			↓	Ni I (86)
11	4419·44	62	4423·48	Ca I (4)	Fe I (350)		
		63	4455·75	↓			
12	4476·10	64	4477·78		↓		
13	4524·77	65	4523·90				Co I (150)
		66	4553·78				
14	4564·72	67	4567·01				↓
15	4636·07						Co I (156)
16	4698·95						
17	4777·68						↓
18	4913·00				Fe I (318)		
19	4950·35						
20	5005·71				↓		
21	5044·50				Fe I (114)		
22	5104·79				Fe I (1)		
23	5165·29	68	5163·55	Mg I (2)			
		69	5179·28	?			
24	5219·68	70	5224·99		Fe I (15)	Fe I (383)	Fe I (553)
25	5266·30	71	5265·04			↓	
26	5321·26	72	5323·21				
27	5365·63	73	5365·50				
28	5386·53						↓
30	5448·93						
31	5493·63				↓		
32	5524·76						Co I (38)
33	5590·46						Co I (90)
34	5673·83			Na I (6)			
35	5888·86			Na I (1)			
36	5972·04			Si II (4)			↓
37	6152·76			Na I (5)			
38	6239·91			Si I (27), (28)			Co I (37)
39	6347·96			Si II (2)			

Table 7

Relative intensities of the spectral lines at the brightest point (Spectrum No. 56)

No.	Intensity	No.	Intensity	No.	Intensity
1	43	25	72	50	57
2	100	26	71	51	46
3	92	27	?	52	48
4	49	28	?	53	55
5	44	29	?	54	45
6	45	30	?	55	51
7	54	31	49	56	42
8	52	32	50	57	43
9	49	33	59	58	45
10	58	34	55	59	32
11	53	35	101	60	83
12	58	36	47	61	64
13	50	37	56	62	72
14	52	38	57	63	72
15	50	39	65	64	73
16	53	40	58	65	85
17	51	41	64	66	59
18	44	42	70	67	58
19	40	43	54	68	57
20	49	44	66	69	57
21	47	45	67	70	?
22	47	46	132	71	?
23	84	47	121	72	?
24	68	48	49	73	?
		49	56		

this meteor spectrum at the height of 89 km. The detailed and extensive analysis of this spectrum is still in progress.

5. Preliminary Conclusions

As to the observational optical study of meteor physics, our experience has taught us that the accumulation of more spectrograms of high quality is important at the present stage. This opinion demands a longer observation time in practice, and we are planning to convert our automatic photographic cameras, situated at Dodaira, into spectral ones, with the use of transmission gratings. This will make a long time of observation easier and simpler. The grating camera is far more useful than the prism camera because the zero-order image of the former can be treated as that of a direct photograph, if the meteor is bright enough. We think such an improvement will be useful in every branch of meteor study.

Another important item is to study meteor spectra in the infrared region, especially the behavior of the Si II lines at 6347 Å and 6371 Å. We think the study of the meteor's infrared spectrum will give valuable information about the abundance of silicon, and new clues as to the relation between the radiation mechanism of meteors and the upper atmosphere.

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https://doi.org/10.1017/S0074180900019677 Published online by Cambridge University Press