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A STUDY OF SPECTRAL LINE IDENTIFICATIONS IN PERSEID METEOR SPECTRA

Ian Halliday

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A Study of Spectral Line Identifications in Perseid Meteor Spectra

IAN HALLIDAY

ABSTRACT—A detailed list of spectral line identifications is derived from the study of five Perseid meteor spectra. A total of 229 features are identified in the region from 3680 A to 8710 A. It is shown that lines of N II, O II, and Sr II are present, and probably also lines of Sr I, Ba I, and Ba II, in addition to lines of other atoms and ions previously identified. The high excitation energies required for the lines of N II and O II are discussed. Additional wavelengths may be expected to appear on spectra of higher dispersion or by further extensions of the observations to the ultraviolet and infrared.

RÉSUMÉ—La liste détaillée d'identifications de raies spectrales provient de l'étude de cinq spectres météoriques des Perséides. On a identifié un total de 229 traits particuliers dans la région allant de 3680A à 8710A. On a relevé la présence de lignes N II, O II et Sr II, de même que la présence probable des lignes de Sr I, Ba I et Ba II, en plus des lignes d'autres atomes et ions identifiées antérieurement. Les grandes énergies d'excitation requises pour les lignes N II et O II y sont discutées. On peut prévoir la découverte de longueurs d'ondes additionnelles dans des spectres de plus grande dispersion ou encore par des observations plus poussées au sein de l'ultraviolet et de l'infrarouge.

Introduction

Among the meteor spectra photographed at the Meanook and Newbrook meteor observatories, Alberta, Canada, during 1958, 1959, and 1960 are several excellent spectra of Perseid meteors. The detailed analysis of the atomic emission lines observed in these spectra leads to a table of line identifications which is considerably more extensive than any such table previously published. This study is devoted exclusively to these spectral line identifications. Some of the spectra also exhibit interesting variations in intensity which will be discussed in a later paper.

Observational Material

The observatories themselves have been described by Millman (1959a) and the meteor spectrographs with which the spectrograms were secured have been described by Halliday (1958). The observing staff at the observatories consisted of A. A. Griffin, J. M. Grant, V. N. Beck, and T. E. Chmilar, together with T. L. Pearson and E. R. Seaquist as summer assistants.

The analysis of spectral lines is based on measurements in the spectra of five different Perseid meteors. For one meteor three different spectrograms contributed to the total number of lines measured. The basic observational material is summarized in Table 1. Successive columns list the date and universal time of the meteor's appearance, the observing station, the camera letter and exposure number of the spectrogram, and the emulsion used in the camera. The next columns list the number of

TABLE 1.—OBSERVATIONAL DATA

Date			Universal Time			Station	Exposure Number	Emulsion*	Grating, grooves per mm	Dispersion		Shutter, breaks per second
y	m	d	h	m	s					I order	II order	
1958	8	12	8	01	15	Newbrook	T 570	Tri-X	400	115	61	none
						Newbrook	U 570	IR	400	113		none
						Newbrook	WY	I-D	80	1950		11
1959	8	13	9	27	55	Newbrook	S 766	Tri-X	400	117	60	none
1960	8	12	5	28		Newbrook	H 1582	IR	400	119		24
1960	8	12	8	18	53	Meanook	B 668	I-D	300	105		12
1960	8	13	6	14	31	Meanook	A 678	I-D	300	106	50	12

*Tri-X — Kodak Tri-X Aerecon film.
IR — Kodak Infrared Aerographic film.
I-D — Kodak Spectroscopic I-D emulsion on film or plates.

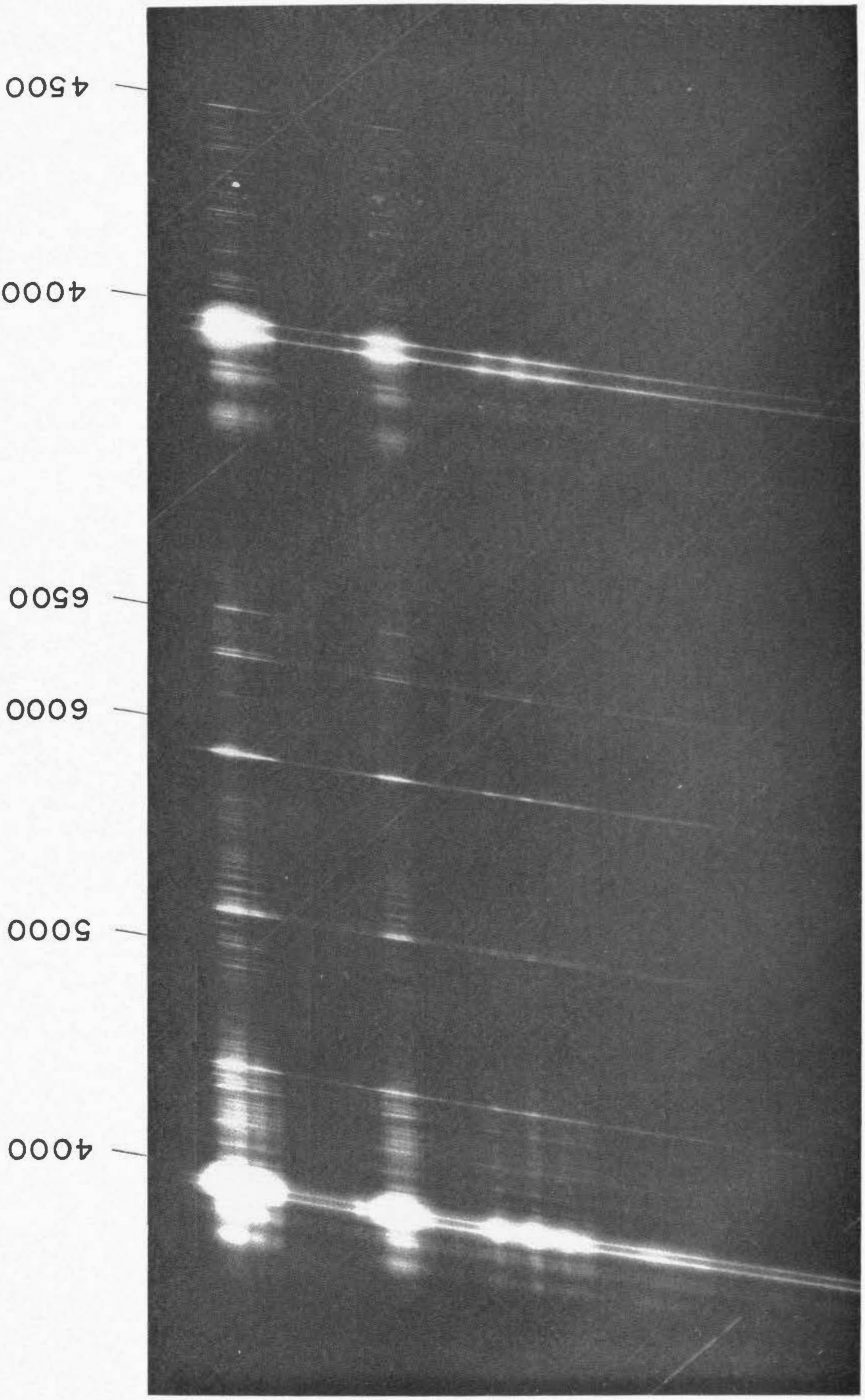

Figure 1. Exposure T570, August 12, 1958

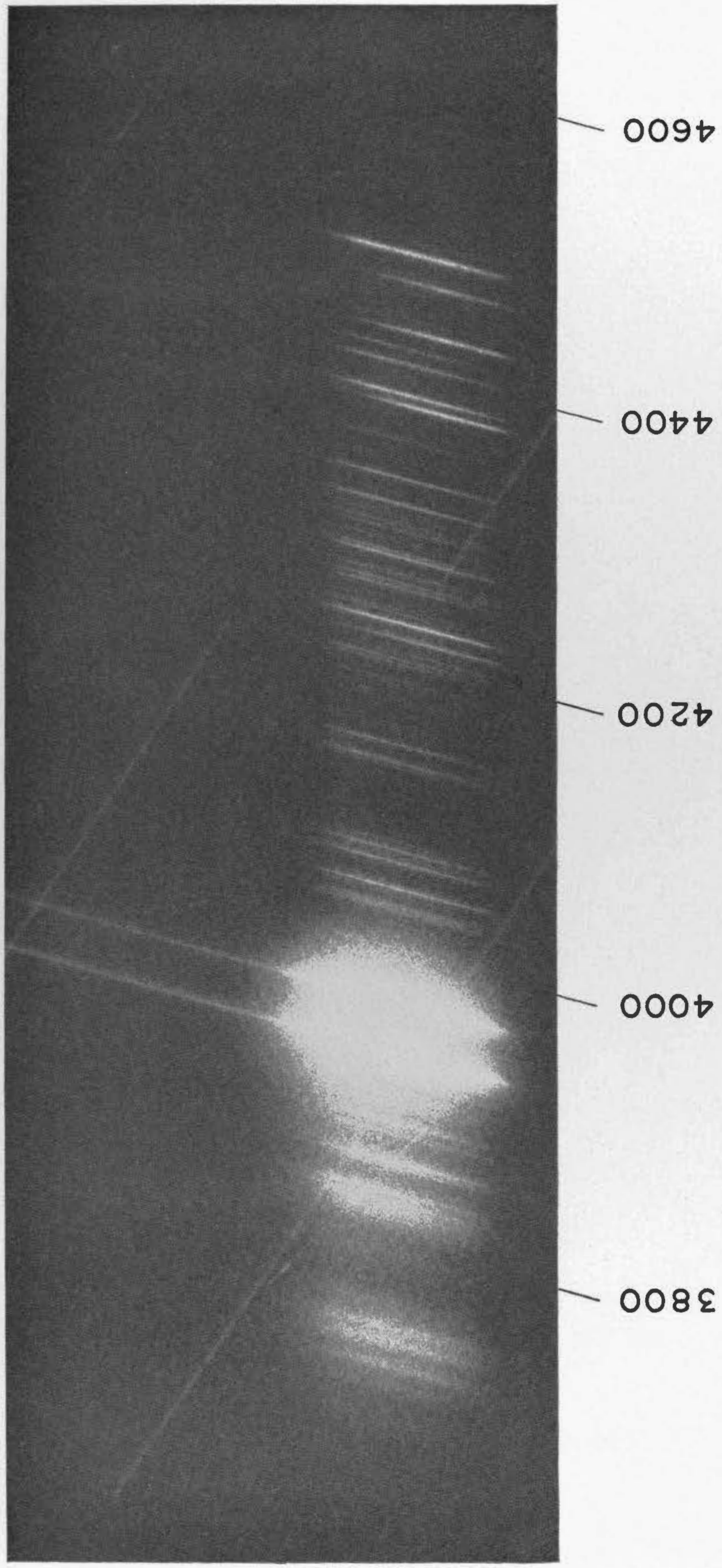

Figure 2. Exposure S766, August 13, 1959

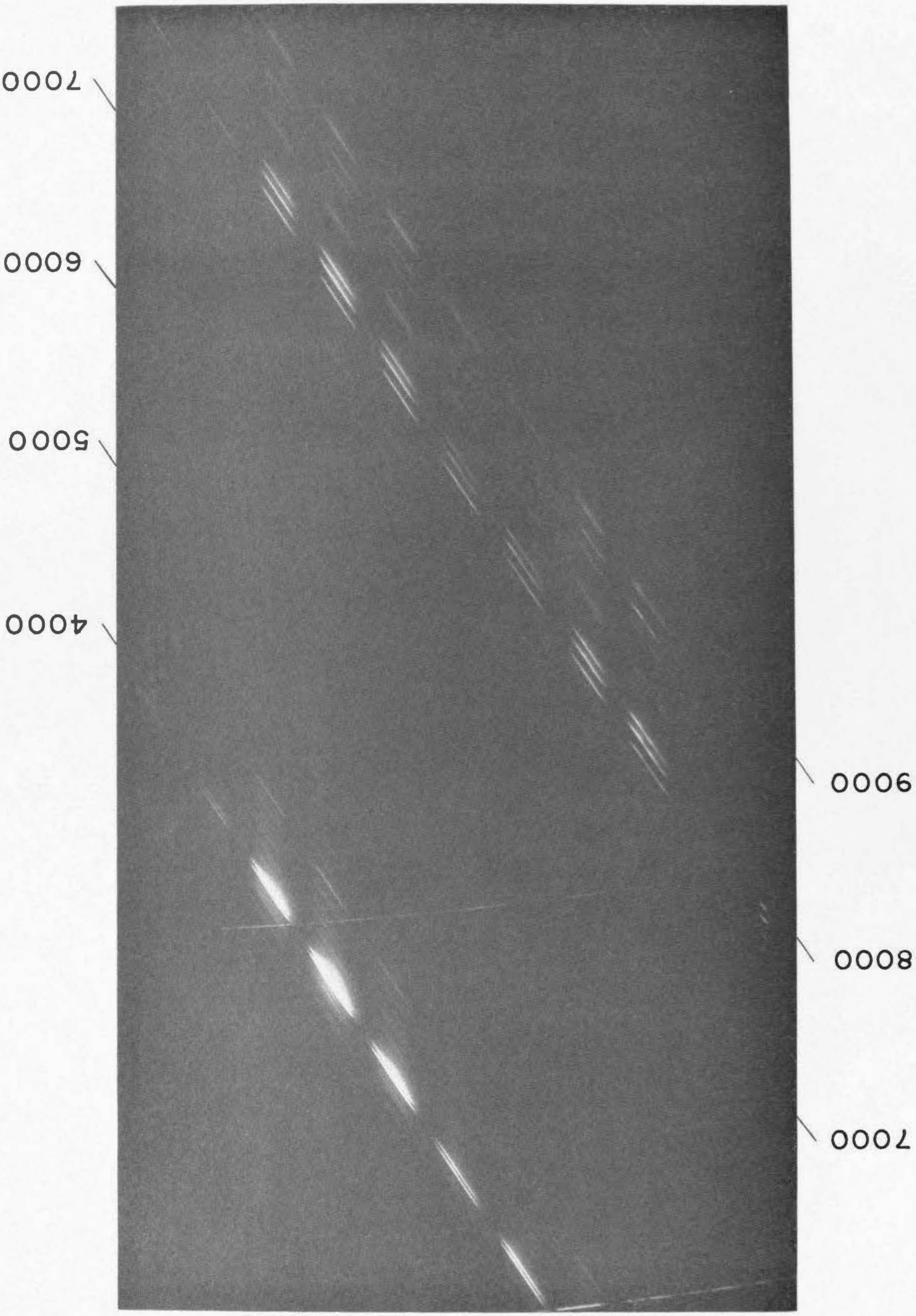

Figure 3. Exposure H1582, August 12, 1960.

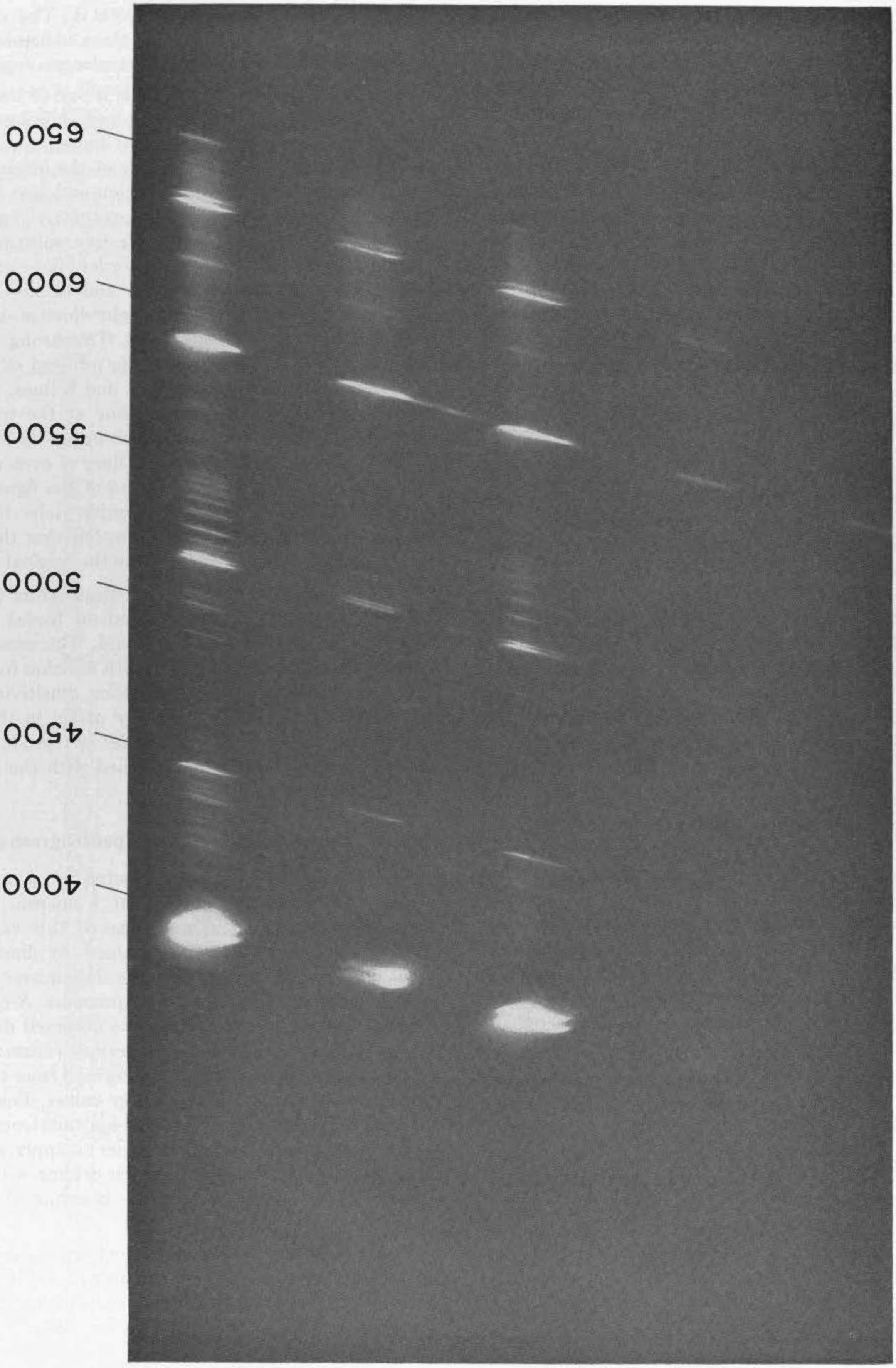

Figure 4. Exposure A678, August 13, 1960.

lines per mm on the objective grating for each camera and the dispersion of the original spectrogram in A/mm for the first order and also for the second order whenever this was used in the reductions. The final column indicates the presence or absence of a rotating shutter in front of the grating by indicating the approximate number of times per second that the trail was interrupted for those cameras which were equipped with a shutter.

Reproductions of four of the meteor spectra appear in Figures 1 to 4. The figures are all arranged with increasing wavelength to the right to facilitate comparisons. Wavelength markers appear at the edges of the figures. In Figures 1 and 4 the direction of motion of the meteor is toward the top of the figure while in Figures 2 and 3 the direction of the meteor's motion is toward the bottom of the figure.

Figure 1. Exposure T570. This shows the first-order spectrum and the blue end of the second-order spectrum of a spectacular Perseid meteor with numerous flares. Variations along the length of the trail represent variations in the luminosity of the meteor as the camera which took this photograph had no occulting shutter. Among the strongest lines in the spectrum are the following, from left to right: the K and H lines of Ca II in the first order at 3933 and 3968 A respectively; λ4481, due primarily to Mg II; a strong pair at 5170 and 5183 A due to Mg I, with some blending from Fe I; the sodium D lines near 5893 A; a pair of lines due to Si II at 6347 and 6371 A; and the Hα line of hydrogen at 6562 A. To the right, the lines of K and H dominate the second-order spectrum.

This is meteor spectrum number 275 in Millman's (1959b) world list of meteor spectra. It proved to be the most useful of the group of five meteors under consideration. A total of seven spectrographs photographed at least a portion of the spectrum. Exposure U570 showed some infrared features, although unfortunately most of the infrared region lay just outside the field of the camera. Camera WY, using a very fast, low-dispersion system, recorded the auroral green line at 5577 A. The other spectrograms did not record any lines not detected on exposure T570.

Figure 2. Exposure S766. The figure shows the second-order spectrum in the blue region only. The strong pair of lines are again the H and K lines of Ca II while the strong line at the right is λ4481 of Mg II. The blaze of the grating is such that the blue end of the second order has high intensity but the efficiency drops rapidly in the region just beyond 4500 A, where meteor spectra contain no strong lines. The terminal flare of this meteor was likely the brightest of the group, but the first-order portion of the spectrogram has generally inferior definition. The second order, reproduced in Figure 2, has excellent definition between 3850 A and 4500 A. The strong intensity and high dispersion made this a valuable spectrogram for detailed study of this wavelength region.

Figure 3. Exposure H1582. This is one of the best infrared spectrograms in existence and shows essentially all strong lines in this region that have been identified in meteor spectra. The sensitivity of the infrared emulsion is high in the blue-violet region and also in the infrared, but is quite low in the green, yellow, orange and red regions. This causes the effective splitting of the spectrum into two parts, the first-order blue-violet region at the left, dominated by the H and K lines, and the first-order infrared region at the right which is overlapped with the second-order blue-violet. The strong triplet of lines near the right consists of the infrared oxygen line at 7774 A and the second-order H and K lines. Note the greater strength of the oxygen line at the top of the figure before the strong flare which brings up the H and K lines. Except for H and K, all lines of even moderate intensity in the right-hand portion of the figure are infrared lines rather than second-order violet lines. The sensitivity in the visual region is so low that the intense Na D lines are barely detectable on the original negative.

Figure 4. Exposure A678. This spectrogram (and similarly exposure B668) was secured on Kodak Spectroscopic I-D emulsion on glass plates. The camera focal length was 12 inches compared with 8 inches for Figures 1 to 3. Because of different emulsion sensitivity curves this spectrum proved particularly useful in the yellow to red regions. Only the first order is reproduced. The strong lines can readily be matched with the strongest features in Figure 1.

Measurement of the Spectrograms

The spectrograms were measured in a measuring engine reading to an accuracy of 1 micron, although errors in setting will normally exceed this value. Preliminary wavelengths were obtained by linear interpolation between two wavelengths chosen near the ends of the spectral region under measurement. A correction curve was then drawn up from the observed differences between these values and the laboratory values for many of the stronger lines, and corrections read from this curve were then applied to all preliminary values. The spectrograms have sufficiently high dispersion and strong enough intensity to make this process easier to apply and more accurate than is usually the case in dealing with fainter spectra of low dispersion, where blending of spectral lines is more serious.

For lines below 4500 A the second-order spectra were generally more useful than the first-order and were given higher weight in forming average wavelengths when the same line was measured in both orders. When close lines were blended in the first order, but were resolved in the second order, the second-order measurements were adopted. Faint lines were sometimes measurable in the first order but not in the second.

After the measurements had been completed it was found that a number of very faint lines could be detected on enlarged positive prints which were too faint to see with the measuring engine. These lines often stand out most clearly by sighting along the print at a small angle to the plane of the paper. Approximate wavelengths were obtained for these lines by interpolation between nearby features using a millimeter scale and estimating distances on the enlargements to 0.1 mm. Additional evidence for the presence of these faint lines was often available from microphotometer tracings of exposure T570.

The measured wavelengths and the adopted identifications are shown in Table 2. The results are presented in detail in the hope that the table may serve as a convenient reference for identifications in the spectra of other fast meteors.

TABLE 2.—MEASURED WAVELENGTHS AND IDENTIFICATIONS

λ_{meas}	Atom or Ion	Mult.	λ_{lab}	Camera
3683	Fe I	5	3679.9	
			3683.1	
	Fe I	21	3687.5	
3706.1	Fe I	5	3705.6	
			3707.8	
	Fe I	21	3709.2	
3719.0	Fe I	5	3719.9	
3726	Fe I	21	3727.6	
3734.4	Fe I	5	3737.1	
	Fe I	21	3734.9	
3746.2	Fe I	5	3745.6	
			3748.3	
	Fe I	21	3749.5	
3762	Fe I	21	3758.2	
			3763.8	
			3767.2	
3798.8	Fe I	21	3795.0	
			3798.5	
			3799.5	
3815.0	Fe I	45	3815.8	S
3820	Fe I	20	3820.4	
3826.3	Fe I	20	3825.9	S
	Fe I	45	3827.8	
3829	Mg I	3	3829.4	
3832	Mg I	3	3832.3	
	Fe I	20	3834.2	
3837.6	Mg I	3	3838.3	
3856	Si II	1	3856.0	
	Fe I	4	3856.4	
3859.2	Fe I	4	3859.9	
3865	Si II	1	3862.6	
	Fe I	20	3865.5	
3872.7	Fe I	20	3872.5	
3877.9	Fe I	4	3878.6	
	Fe I	20	3878.0	
3886.4	Fe I	4	3886.3	
3896	Fe I	4	3895.7	
	Fe I	20	3898.0	
3899.2	Fe I	4	3899.7	S
3906	Si I	3	3905.5	
	Fe I	4	3906.5	
3919	Fe I	4	3920.3	
	Fe I	20	3917.2	
3923.6	Fe I	4	3922.9	S
3934.3	Ca II	1	3933.7	
3968.6	Ca II	1	3968.5	
	Fe I	43	3969.3	
4004.8	Fe I	43	4005.2	
4021.5	Fe I	278	4021.9	S
4031.1	Mn I	2	4030.8	S
4033.4	Mn I	2	4033.1	S
4034.8	Mn I	2	4034.8	S
4040.5	Mn I	5	4041.4	
4046.0	Fe I	43	4045.8	
4058.5	Fe I	558	4058.2	S
4063.8	Fe I	43	4063.6	
4067.7	Fe I	358	4067.0	S
	Fe I	559	4068.0	
4072.0	Fe I	43	4071.7	
	O II	10	4072.2	
4077.3	Sr II	1	4077.7	
	O II	10	4075.9	
	Fe I	558	4076.6	
4083.8	Mn I	5	4082.9	S
			4083.6	
	Fe I	559	4085.3	
	Fe I	698	4084.5	
4106.3	Fe I	354	4107.5	S
4109.5	N I	10	4110.0	S
	Fe I	357	4109.8	
4118.7	Fe I	801	4118.5	
4128.6	Si II	3	4128.1	
4131.3	Si II	3	4130.9	
	Fe I	43	4132.1	
4143.7	Fe I	43	4143.9	
	Fe I	523	4143.4	
4154.6	Fe I	354	4156.8	
	Fe I	355	4154.5	
	Fe I	694	4154.8	
	Fe I	695	4153.9	
4167.5	Mg I	15	4167.3	
4174.0	Fe I	19	4172.7	
			4174.9	
	Fe I	354	4175.6	
	Fe II	27	4173.4	
4178	Fe II	28	4178.9	
4181.8	Fe I	354	4181.8	S
4184.4	Fe I	355	4184.9	S
4187.7	Fe I	152	4187.0	
			4187.8	
4191.5	Fe I	152	4191.4	S
4195.5	Fe I	693	4195.3	S
			4196.2	
4198.7	Fe I	152	4198.3	
	Fe I	522	4199.1	
4202.0	Fe I	42	4202.0	
4206.4	Fe I	3	4206.7	
4211	Fe I	152	4210.4	
4216.2	Fe I	3	4216.2	
	Sr II	1	4215.5	
4222.7	Fe I	152	4222.2	
4226.9	Ca I	2	4226.7	
	Fe I	693	4227.4	
4233.1	Fe II	27	4233.2	
	Fe I	3	4232.7	
	Fe I	152	4233.6	
4235.8	Fe I	152	4235.9	
4246.5	Fe I	693	4247.4	
4250.7	Fe I	42	4250.8	
	Fe I	152	4250.1	
4254.5	Cr I	1	4254.3	
4258.2	Fe I	3	4258.3	S
4260.5	Fe I	152	4260.5	
4268.0	Fe I	482	4267.8	S
4271.6	Fe I	42	4271.8	
	Fe I	152	4271.2	

TABLE 2.—MEASURED WAVELENGTHS AND IDENTIFICATIONS—*Continued*

λ_{meas}	Atom or Ion	Mult.	λ_{lab}	Camera
4274.8	Cr I	1	4274.8	
4282.4	Fe I	71	4282.4	
	Ca I	5	4283.0	
4289.8	Cr I	1	4289.7	S
	Ca I	5	4289.4	
4291.7	Fe I	3, 41	4291.5	S
4294.1	Fe I	41	4294.1	
4299.4	Fe I	152	4299.2	
	Ca I	5	4299.0	
4303	Ca I	5	4302.5	
	Fe II	27	4303.2	
4308.0	Fe I	42	4307.9	
	Ca I	5	4307.7	
4315.1	Fe I	71	4315.1	
	Fe II	32	4314.3	
4318	O II	2	4317.1	
			4319.6	
	Ca I	5	4318.7	
4325.8	Fe I	42	4325.8	
4338.5 b	H I	1	4340.5	
	Fe I	41	4337.0	
	Cr I	22	4339.4	
4344.7	Cr I	22	4344.5	S
4351.1	Mg I	14	4351.9	
	Fe I	71	4352.7	
	Fe II	27	4351.8	
	O II	2	4349.4	
	Cr I	22	4351.8	
4368.6	O I	5	4368.3	
	Fe I	41	4367.9	
	Fe II	28	4369.4	
4376.1	Fe I	2	4375.9	
4383.6	Fe I	41	4383.5	
	Mg II	10	4384.6	
4389.6	Fe I	2	4389.2	
	Mg II	10	4390.6	
4404.7	Fe I	41	4404.8	
4409.7	Fe I	68	4407.7	S
			4408.4	
4415.3 w	Fe I	41	4415.1	
	Fe II	27	4416.8	
	O II	5	4414.9	
			4417.0	
4422	Fe I	350	4422.6	
4427.4	Fe I	2	4427.3	
	Mg II	9	4428.0	
4434	Ca I	4	4435.0	
			4435.7	
	Fe I	2	4435.2	
	Mg II	9	4434.0	
4442.7	Fe I	68	4442.3	
	Fe I	350	4443.2	
4447	Fe I	68	4447.7	
	N II	15	4447.0	
4455.1	Ca I	4	4454.8	
			4455.9	
			4456.6	
	Fe I	350	4454.4	
4461.5	Fe I	2	4461.7	
4468	Fe I	350	4466.6	
			4469.4	
4475.4	Fe I	350	4476.0	S
4481.3	Mg II	4	4481.1	
			4481.3	
	Fe I	2	4482.2	
4489.3	Fe I	2	4489.7	
	Fe II	37	4489.2	
4493.6	Fe I	68	4494.6	
	Fe II	37	4491.4	
4522	Fe II	37	4520.2	
	Fe II	38	4522.6	
4528	Fe I	68	4528.6	
4549.7	Fe II	38	4549.5	
4555.3	Fe II	37	4555.9	
	Ba II	1	4554.0	
4571.1	Mg I	1	4571.1	
4583.4	Fe II	37	4582.8	
	Fe II	38	4583.8	
	Ca I	23	4581.4	
			4585.9	
4601	Fe I	39	4602.9	
	N II	5	4601.5	
4606	N II	5	4607.2	
	Sr I	2	4607.3	
4619.5	Fe I	821	4619.3	
	Fe II	38	4620.5	
	N II	5	4621.4	
4630.0	Fe II	37	4629.3	
	N II	5	4630.5	
4636	Fe I	554	4637.5	
	Fe I	822	4638.0	
4642–4651	O II	1	4641.8	
			4649.1	
			4650.8	
	N II	5	4643.1	
	Fe I	409	4647.4	
4666.7	Fe I	554	4668.1	
	Fe I	822	4667.5	
	Fe II	37	4666.8	
4676	O II	1	4673.8	
			4676.2	
4691	Fe I	409	4691.4	
4702.9	Mg I	11	4703.0	
	Fe I	821	4705.0	
4733.7	Fe I	38	4733.6	
4823.7	Mn I	16	4823.5	
4861.2	H I	1	4861.3	
	Fe I	318	4859.7	
4870.5	Fe I	318	4871.3	
			4872.1	
4891.3	Fe I	318	4890.8	
			4891.5	
4923.5	Fe I	318	4919.0	
			4920.5	
	Fe II	42	4923.9	
4940	Fe I	16	4939.7	
	Fe I	318	4938.8	
4957.6	Fe I	318	4957.3	
			4957.6	
4967	Fe I	687	4966.1	
	O I	14	4967.4	
			4967.9	
			4968.8	
4984.1	Fe I	318	4985.6	
	Fe I	984	4985.3	
	Fe I	1066	4983.9	
	Fe I	1067	4982.5	
			4983.3	
5005.6 b	Fe I	318	5006.1	
	Fe I	965	5001.9	
	Fe I	984	5005.7	
	N II	19	5001.1	
			5001.5	
	N II	19, 64	5005.1	
5012	Fe I	16	5012.1	
	Fe I	965	5015.0	
	N II	4	5010.6	
5019.0	Fe II	42	5018.4	
	O I	13	5018.8	
			5019.3	
			5020.1	
5031	Fe I	585	5030.8	
	Fe I	1150	5031.9	
5042.2 w	Si II	5	5041.1	
	Fe I	16	5041.1	
	Fe I	36	5041.8	
	N II	4	5045.1	
5056.7	Si II	5	5056.0	
			5056.4	
5073	Fe I	1094	5074.8	

TABLE 2.—MEASURED WAVELENGTHS AND IDENTIFICATIONS—*Continued*

λ_{meas}	Atom or Ion	Mult.	λ_{lab}	Camera
5110.9	Fe I	1	5110.4	
5141.0	Fe I	16	5142.9	
	Fe I	383	5139.3	
			5139.5	
5152	Na I	8	5148.8	
			5153.4	
	Fe I	16	5150.8	
			5151.9	
5168.5	Mg I	2	5167.3	A
	Fe I	1	5166.3	
			5168.9	
	Fe I	37	5167.5	
	Fe II	42	5169.0	
5173.1	Mg I	2	5172.7	A
	Fe I	36	5171.6	
5183.7	Mg I	2	5183.6	
5194	Fe I	36	5194.9	
	Fe I	383	5191.5	
			5192.4	
	Fe I	1092	5195.5	
5205.3	Fe I	1	5204.6	
	Fe I	66	5202.3	
	Cr I	7	5204.5	
			5206.0	
			5208.4	
5214.3	Fe I	36	5216.3	
	Fe I	553	5215.2	
			5217.4	
5227.9–5235 w	Fe I	37	5227.2	
	Fe I	383	5226.9	
			5232.9	
	Fe I	553, 1090	5229.9	
	Fe II	49	5234.6	
5270.2	Fe I	15	5269.5	
	Fe I	37	5270.4	
	Fe I	383	5266.6	
	Fe II	49	5276.0	
	Ca I	22	5270.3	
5302.6	Fe I	553	5302.3	
5317.4	Fe II	48	5316.8	
	Fe II	49	5316.6	
5328.0	Fe I	15	5328.0	
	Fe I	37	5328.5	
	Fe I	553	5324.2	
	O I	12	5329.0	
			5329.6	
			5330.7	
5340.0	Fe I	37	5341.0	
	Fe I	553	5339.9	
5371.3	Fe I	15	5371.5	
	Fe I	1146	5367.5	
			5370.0	
5383.0	Fe I	1146	5383.4	
5398.0	Fe I	15	5397.1	
5405.4	Fe I	15	5405.8	
	Fe I	1165	5404.1	
5414.6	Fe I	1165	5415.2	
	Fe II	48	5414.1	
5423.7	Fe I	1146	5424.1	
5430.0 b	Fe I	15	5429.7	
			5434.5	
	O I	11	5435.2	
			5435.8	
			5436.8	
5446.7	Fe I	15	5446.9	
	Fe I	1163	5445.0	
5455.0	Fe I	15	5455.6	
5463.1	Fe I	1163	5463.0	
			5463.3	
5476.5	Fe I	1062	5476.6	
5505.7	Fe I	15	5501.5	
			5506.8	
5528.6 b	Mg I	9	5528.4	
	Fe II	55	5534.9	
	Ba I	2	5535.5	
5571.6	Fe I	686	5569.6	
			5572.9	
5577	O I	3 F	5577.4	WY
5587.6	Fe I	686	5586.8	
	Ca I	21	5588.8	
5600.9 b	Ca I	21	5594.5	
			5598.5	
			5601.3	
			5602.8	
	Fe I	686	5603.0	
5615.4	Fe I	686	5615.7	
5624.0	Fe I	686	5624.5	
5657.2	Fe I	686	5658.8	
	Fe I	1107, 1314	5655.5	
5665.9	N II	3	5666.6	
	Si I	10	5665.6	
5679.2	N II	3	5676.0	
			5679.6	
5685.3	Na I	6	5682.6	
			5688.2	
	N II	3	5686.2	
	Si I	11	5684.5	
5709.1	Fe I	686	5709.4	
	N II	3	5710.8	
	Si I	10	5708.4	
5762.1	Fe I	1107	5763.0	
5890.0	Na I	1	5890.0	
5895.9	Na I	1	5895.9	
5942	N II	28	5941.7	
5957.9	Si II	4	5957.6	
	O I	23	5958.5	
			5958.6	
5978.9	Si II	4	5979.0	
6005	N I	16	5999.5	
			6008.5	
6027	Fe I	1018	6027.1	A
	Fe I	1178	6024.1	
6102.7	Ca I	3	6102.7	A
6120.9	Ca I	3	6122.2	
6138	Fe I	169	6136.6	A
	Fe I	207	6137.7	
6157.8	O I	10	6156.0	
			6156.8	
			6158.2	
	Na I	5	6154.2	
			6160.7	
6167.8 b	Ca I	3	6162.2	
	Ca I	20	6166.4	
			6169.1	
			6169.6	
6192	Fe I	169	6191.6	A
6203	Fe I	207	6200.3	A
6229	Fe I	207	6230.7	B
6247.5	Fe I	169	6252.6	
	Fe I	816	6246.3	
	Fe II	74	6247.6	
6301	Fe I	816	6301.5	B
6319	Fe I	168	6318.0	A
	Mg I	23	6318.5	
6337.9	Fe I	62	6335.3	
	Fe I	816	6336.8	
6347.6	Si II	2	6347.1	
6358.1	Fe I	13	6358.7	
6371.3	Si II	2	6371.4	
6398.5	Fe I	168	6393.6	
	Fe I	816	6400.0	
6422	Fe I	111	6421.4	S
6438.8	Ca I	18	6439.1	
6455.9	Fe II	74	6456.4	
	O I	9	6453.6	
			6454.5	
			6456.0	
6462.2	Fe I	168	6462.7	
	Ca I	18	6462.6	

TABLE 2.—MEASURED WAVELENGTHS AND IDENTIFICATIONS—*Concluded*

λ_{meas}	Atom or Ion	Mult.	λ_{lab}	Camera
6483.6	N I	21	6482.7 6483.8 6484.9	
	N II	8	6482.0	
6495.3 b	Fe I	13	6499.0	
	Fe I	168	6495.0	
	Ca I	18	6493.8 6499.6	
	Ba I	6	6498.8	
6525	Ba I	6	6527.3	A
6546	Fe I	268	6546.2	
6562.8	H I	1	6562.8	
6571.7	Ca I	1	6572.8	
6594.5	Fe I	268	6592.9	
	Ba I	6	6595.3	
6680	Fe I	268	6678.0	S
6717.1	Ca I	32	6717.7	
6752	Fe I	111	6750.2	S
7423.7	N I	3	7423.6	U
7442.1	N I	3	7442.3	U
7468.0	N I	3	7468.3	U
7773.9	O I	1	7772.0 7774.2 7775.4	H
8186.9	N I	2	8184.8 8188.0	H
8215.3	N I	2	8210.6 8216.3 8223.1	H
8244	N I	2	8242.3	H
8446.9	O I	4	8446.4 8446.8	H
8498	Ca II	2	8498.0	H
8542.2	Ca II	2	8542.1	H
8592	N I	8	8594.0	H
8630.2	N I	8	8629.2	H
8663	Ca II	2	8662.1	H
8683.4	N I	1	8680.2 8683.3 8686.1	H
8710.2	N I	1	8703.2 8711.7 8718.8	H

b — feature noticeably broad. w — wing observed on red side of feature.

The table is arranged in order of increasing wavelength. Column 1 shows the measured wavelength of each feature. It is quoted to 0.1 A when it is derived from accurate measurement, and to the nearest whole Angstrom unit when it is derived from measurement of the positive prints. Other columns list the identification for each feature, showing the atom or ion concerned, the multiplet number, and the laboratory wavelength, obtained from *A Multiplet Table of Astrophysical Interest* (Moore 1945). Frequently two or more lines are expected contributors to a single feature. The *M.I.T. Wavelength Tables* (Harrison 1939) were also found useful for judging relative intensities of many lines.

Most of the measured wavelengths are based on measurements of spectrogram T570. Certain faint lines were detected only in some of the other spectra, some lines were resolved on S766 which were blended on T570, and the infrared lines depend on U570 and H1582. An entry in the final column indicates that the measured wavelength is derived from a spectrogram other than T570. For example, the triplet due to manganese near 4030 A was blended on T570 but resolved into its three components in the second order of S766. This represents the highest resolution achieved; the separation of the two weaker components is only 1.3 A, which corresponds to a resolution of 35 lines per mm on the original film.

Discussion of Identifications

Since any detailed list of laboratory wavelengths will contain several lines more closely spaced than the best resolution achieved on these spectrograms, the method of selecting the identifications to list for each feature is by no means straightforward. The identifications reflect, to a considerable degree, the previous experience and the judgment of the particular investigator. Differences of opinion are likely to exist among different investigators, particularly in the case of very weak lines which have been recorded on one or only a very few spectrograms.

Table 2 contains many entries, both measured wavelengths and multiplet identifications, which have not been listed previously in meteor spectra. Some of these identifications are admittedly doubtful. On the other hand the dispersion and resolution of these spectrograms has seldom been equalled or surpassed in earlier investigations. A comparison of observed and laboratory wavelengths in Table 2 indicates that, for unblended features, the errors of measurement are only a few tenths of an Angstrom, which is of great help in choosing identifications compared with many earlier spectra in which the errors were often from 1 to 3 Angstroms. For the lines in Table 2 that are quoted to the nearest Angstrom, however, the errors may again be from 1 to 3 A.

Table 2 lists 229 separate features, and the identifications include 458 separate lines as expected contributors. Twelve chemical elements are included in the atomic state and eight of them are also listed in the first stage of ionization. In all, 160 different multiplets are involved and these have been collected in Table 3, where the elements are arranged in order of increasing atomic weight.

TABLE 3.—MULTIPLETS IDENTIFIED IN TABLE 2.

Atom or Ion	Multiplets
H I	1
N I	1, 2, 3, 8, 10, 16, 21
N II	3, 4, 5, 8, 15, 19, 28, 64
O I	1, 4, 5, 9, 10, 11, 12, 13, 14, 23, 3F
O II	1, 2, 5, 10
Na I	1, 5, 6, 8
Mg I	1, 2, 3, 9, 11, 14, 15, 23
Mg II	4, 9, 10
Si I	3, 10, 11
Si II	1, 2, 3, 4, 5
Ca I	1, 2, 3, 4, 5, 18, 20, 21, 22, 23, 32
Ca II	1, 2
Cr I	1, 7, 22
Mn I	2, 5, 16
Fe I	1, 2, 3, 4, 5, 13, 15, 16, 19, 20, 21, 36, 37, 38, 39, 41, 42, 43, 45, 62, 66, 68, 71, 111, 152, 168, 169, 207, 268, 278, 318, 350, 354, 355, 357, 358, 383, 409, 482, 522, 523, 553, 554, 558, 559, 585, 686, 687, 693, 694, 695, 698, 801, 816, 821, 822, 965, 984, 1018, 1062, 1066, 1067, 1090, 1092, 1094, 1107, 1146, 1150, 1163, 1165, 1178, 1314
Fe II	27, 28, 32, 37, 38, 42, 48, 49, 55, 74
Sr I	2
Sr II	1
Ba I	2, 6
Ba II	1

Some of the multiplets are represented only as partial contributors to a single blended feature. In such cases, or even when it is a suspected contributor to several features or the only contributor to an extremely weak line, the presence of the multiplet may be considered doubtful. Table 4 lists 41 multiplets which, on this basis, are considered to be the doubtful entries in Table 3.

Numerous lists of line and multiplet identifications in meteor spectra have been published. Among them, ones published by Millman (1953, 1956, 1961) and by Russell (1960) are perhaps the most useful for purposes of comparison.

TABLE 4.—DOUBTFUL MULTIPLET IDENTIFICATIONS

Atom or Ion	Multiplets
N I	10
N II	4, 19, 64
O I	13
O II	5, 10
Na I	8
Mg I	23
Mg II	9, 10
Si I	3, 10, 11
Ca I	20, 23
Fe I	62, 66, 111, 358, 482, 554, 585, 687, 694, 695, 698, 821, 822, 1018, 1066, 1090, 1092, 1314
Fe II	32, 48, 55
Sr I	2
Ba I	2, 6
Ba II	1

In the detailed discussion below, particular attention is directed to those identifications which involve an atom or ion not previously identified in meteor spectra. Many of the new multiplets in Table 2 are additional multiplets of atoms whose presence was already well established in other spectra and it was to be expected that more intense spectra with improved resolution would add significantly to the number of multiplets. This is particularly true of atomic iron, which has such a complex spectrum, and which has already accounted for the identification of a majority of lines in previous meteor spectra. No particular justification is required, therefore, for the addition of a multiplet such as Fe I, 1146, which contributes two unblended lines and one blended line in spectrum T570.

On the other hand, very careful consideration is required before adding a new atom to the list. This should include consideration not only of the measured lines to be attributed to the atom, but also a reasonable explanation for not observing other equally strong lines of the spectrum if such lines exist. Furthermore, the possible presence of the atom in observable quantities in meteors (or the upper atmosphere) should be considered. Somewhat less strict considerations apply before adding to the list of identifications lines that are due to the first ionized stage of an atom known to be present in the neutral state. With these criteria in mind, attention will now be given to each atom or ion identified, and later to some others which remain undetected.

H I. The Hα line was first identified by Millman (1953). Hβ and Hγ are also contributors to these Perseid spectra.

N I. The strong infrared multiplets identified by Millman (1953) and Millman and Halliday (1961) are found, as well as a few others in the visible region.

N II. One of the most interesting results of this analysis is the identification of lines due to ionized nitrogen. A line of moderate strength at 5679 A is observable on both T570 and A678 and is identified as λ5679.56 due to multiplet 3 of N II. A weaker member of the same multiplet at 5676.02 A probably also contributes to the same feature. No other reasonable identification is available for this feature. A microphotometer trace of T570, on a linear intensity scale, is shown in Figure 5, which shows that λ5679 is well separated from the feature near 5685 A (which is largely due to sodium but should also contain another line of N II, 3 and possibly a line of neutral silicon).

Ionized nitrogen is listed as a contributor to 15 features in Table 2. In only 2 cases, λλ5679 and 5942, is it the only identification listed for the feature, but in several cases the line appears too intense to be accounted for entirely by the other contributors. Furthermore, there are no serious omissions where a strong line of N II is known to exist but is lacking in the meteor spectra (except for λ3995 which is lost in the halation around the H and K lines).

The presence of molecular nitrogen in the atmosphere at meteor heights is well established, hence there is no problem in accounting for the presence of nitrogen. Strong lines due to neutral atomic nitrogen, as well as the first positive group of bands of molecular nitrogen, are observed in meteor spectra. The significant feature is the high excitation energies required for the lines of N II. They range from 20.6 ev to 23.1 ev for the upper states of the observed lines, with one other doubtful contributor at 27.8 ev. These values, together with the lines of O II discussed below, are much higher than any previous excitation energies, which went only as high as 12 to 13 ev for the Balmer hydrogen lines and some of the lines due to N I, O I, and Si II.

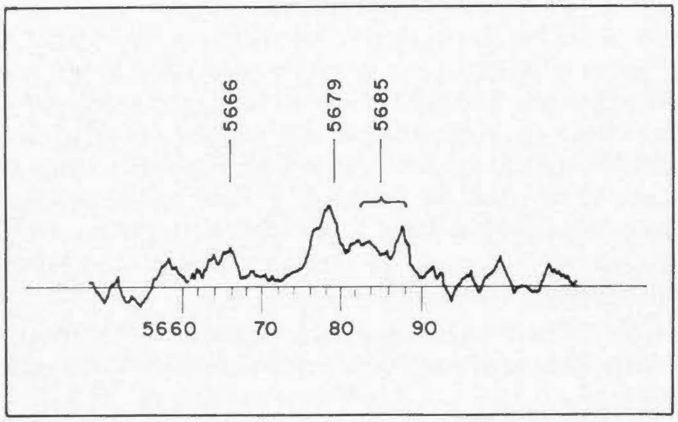

Figure 5. Intensity trace of N II line at 5679 A, exposure T570

The lines of N II are observed in the terminal flares near the bottom of the trails, at heights of about 80 km. At this height atmospheric nitrogen is in molecular form, so that the total energy required to dissociate the molecule, ionize the atom, and excite the observed lines amounts to 45 ev. This is very high compared with other lines observed in meteor spectra but still represents only about 10 per cent of the kinetic energy of an average atom from a fast meteor. In addition, it is possible that the dissociation, ionization, and excitation are accomplished by successive collisions of atmospheric particles with meteor atoms rather than all by the initial collision.

O I. Strong lines of O I are observed in the infrared region and several weaker multiplets are identified in the visual region. The auroral green line was observed on one spectrogram of spectrum 275. Its presence in meteor spectra has been discussed previously (Halliday 1960). The identification of O I, 10, at 6157 A, results from a comparison of the line with the Na D lines on plates taken with the I-D emulsion. The Tri-X and I-D emulsions both have some minor maxima and minima in their sensitivity curves in the red. Near 6160 A the I-D emulsion is superior to Tri-X because one of the maxima for the I-D emulsion is in this vicinity. The feature has sometimes been attributed to Na I, 5, one of the doublets with 6 A separation which is centred almost exactly on the more closely spaced triplet of O I, 10. Some of the spectrograms which resolve Na D show λ6157 as a sharp line, indicating that the dominant contributor, in these cases at least, is O I, 10 rather than Na I, 5. It may also be noted that the line is comparatively weak in the spectra of slower meteors where O I, 10 would not be expected because of its high excitation potential.

O II. Seven features are listed with lines of O II as contributors. The only unblended member of this group is a very weak line at 4676 A, due to O II, 1. The presence of O II, 1 as well as N II, 5, is required to account for the width of a diffuse feature which extends from 4642 to 4651 A. The presence of lines due to O II is somewhat more difficult to establish, owing to the blending effects of other lines, than was the case for N II. The excitation energies for O II are slightly higher than for N II, ranging from 22.9 to 28.6 ev for the four multiplets listed in Table 3. The two cases are sufficiently similar, however, that with the presence of N II established, lines due to O II should definitely be expected. While oxygen is a less abundant atmospheric constituent than nitrogen, it must be expected that the meteor will contribute many oxygen atoms that were present in silicates and other compounds in the meteor.

Na I. The D lines are strong in all cases and well resolved in some of these spectra. Three other multiplets of Na I are contributors to blended features.

Mg I. All the usual multiplets of Mg I are identified in these spectra.

Mg II. In addition to the very strong line at 4481 A two other multiplets of Mg II are expected contributors.

Si I. The presence of Si I lines in these spectra remains doubtful, in spite of the prominence of Si II. Three multiplets are listed as possibly present but the absence of a line near 4102 A, the location of multiplet 2, casts doubt on the presence of the other Si I lines.

Si II. Five pairs of lines are identified with Si II including the strong pair near 6350 A.

Ca I. While 11 multiplets of Ca I are listed in Table 3 only 2 or 3 of these are at all prominent. Most of the other multiplets are blended with lines due to other elements.

Ca II. The H and K lines of Ca II are much the strongest lines in Perseid spectra and are often so overexposed as to make difficult the detection of any other lines within 30 or 40 A. Multiplet 2 is prominent in the infrared region.

Cr I. Chromium is a minor contributor to meteor pectra but a few lines of the strongest multiplets are definitely present.

Mn I. As for Cr I, a few of the strongest multiplets of Mn I are observed. The triplet near 4030 is the most prominent feature due to Mn I.

Fe I. Lines of Fe I dominate the identifications in almost all meteor spectra. These spectra add many multiplets not previously identified, particularly among the higher multiplets with numbers above 500.

Fe II. Some moderately strong lines are due primarily to Fe II and 10 multiplets are listed in Table 3. Some of them are doubtful, and it is noted that the lines of Fe II appear to be involved in blends more frequently than lines of most other atoms or ions.

Sr I. The strongest line of Sr I is suggested as a contributor to a weak feature at 4606 A. The other possible contributor is a line of N II, 5, which, however, is listed with low enough intensity that it would not be expected to show unless it were reinforced by some other line. The more certain identification of Sr II lends some support to the presence of Sr I.

Sr II. The strong line at 4077 A is present in T570 and S766. While two other contributors are listed in Table 2, the precision of measurement, particularly in S766, indicates that the main contributor is Sr II, not Fe I or O II. The other strong line of Sr II, at 4215 A, is confused by the presence of a strong line at 4216 A due to Fe I, 3.

Ba I and Ba II. Among the doubtful identifications are two multiplets of Ba I and one of Ba II. The only line of barium which is not listed as a blend is 6525 A, a very weak feature observed on both A678 and S766. The wavelength agreement is only fair, as the suggested identification is the line of Ba I, 6, at 6527.3 A. The magnesium line at 5528 A is observed to have a wing on the red side which can be accounted for by a weak, and therefore doubtful, multiplet of Fe II, (number 55) or by the strong line of Ba I, 2, at 5535 A. The strongest line of Ba II, at 4554 A, is blended with one of the stronger lines of Fe II at 4555 A and hence positive identification of Ba II is lacking.

Among the elements of higher atomic weight, however, barium is perhaps the least surprising one to encounter. Its location in the periodic table is analagous to the positions of magnesium, calcium, and strontium, all of which are present in meteor spectra. The abundances of barium determined in the solar atmosphere (Goldberg, Müller and Aller 1960) and in the pure silicate portions of meteorites (Krinov 1960) are less than the abundances of strontium by a factor of only 3, in spite of the considerable difference in their atomic numbers. It is also recalled that in a few stellar spectra the line of Ba II at 4554 A is so strong that the stars have been called Ba II stars (Bidelman and Keenan, 1951).

It is suggested then, that barium may be present in meteor spectra although its presence is not considered to be established.

Elements Not Detected

A few comments are required regarding certain elements whose presence was not detected in these Perseid spectra. In this connection it is to be noted that the definition of these spectra in the ultraviolet region, particularly below 3800 A, is not very good. In addition the transmission of the optics limits the observable spectrum, so that very little can be detected below 3700 A. Some meteor spectra, photographed with other instruments, have had superior definition and transmission in the ultraviolet region. As a result some lines could be identified in this region which are unobservable on our spectrograms.

No lines of Al I were found in these spectra. The strong pair at 3944 and 3961 A are so close to the H and K lines of Ca II that it is impossible to search for them near strong bursts where H and K are heavily overexposed. From weaker portions of the trails, however, it is possible to conclude that the lines of Al I, if present, are not as strong as the strongest eight or ten lines of Fe I in the blue region.

No features were found which required the presence of Co I or Ni I in these Perseid spectra. To some extent this may be due to the performance of the instruments in the ultraviolet region. Lines of both Co I and Ni I would be expected from iron meteorites. Both have also been claimed at times in the spectra of shower meteors but such identifications receive no support from these intense and detailed Perseid spectra.

Among the elements still unidentified in meteor spectra, yet which might be expected to have reasonable abundances, are phosphorus, sulphur and potassium. The strong lines of neutral phosphorus are all in the infrared, beyond the limit of the emulsions used for meteors. Sulphur would not be detected easily, but multiplet 2, near 4695 A, should be kept in mind. The strong doublet of neutral potassium is near 7700 A, which is an accessible region of the spectrum, but one which may be confused by the second-order ultraviolet lines until filters are used to eliminate the second order. The other possible doublet is so close to the Fe I line at 4045 A that it would require somewhat higher dispersion than has yet been achieved to detect the presence of comparatively weak potassium lines.

The lines and bands of nitrogen which are observed in meteor spectra represent an atmospheric constituent excited by the passage of the meteor. Some fraction of the oxygen radiation will also be due to atmospheric oxygen. With emulsions extending well into the red the strong lithium line at 6707 A might be found if a careful search is made in this region.

Conclusions

The identifications listed in Tables 2 and 3 have been compiled from five Perseid meteor spectra. They should prove equally useful in the analysis of the spectra of other fast meteors. For slow meteors many of these features will not be observed, particularly lines from ionized atoms and those lines from neutral atoms which require excitation energies greater than about 7 ev. Essentially all the lines found in slow meteors, however, are also found in fast meteors, hence by dropping the high-excitation lines the present table should also prove useful for slow meteors.

Future additions to this list are likely to arise from the following sources. Many lines might be added in the ultraviolet region when a sufficiently bright meteor spectrum is obtained with one of the spectrographs with good transmission below 3700 A. Some other lines might be added in the near infrared, although the indications from existing spectra suggest that this will not become a region in which the lines are generally crowded.

In the visible region, from about 4000 A to 6600 A, further additions to the list are likely to be minor ones until such time as a very bright meteor is photographed with a first-order dispersion of about 40 A/mm. Meteor spectrographs capable of this dispersion are in operation on the Canadian programs conducted by the National Research Council and by the Dominion Observatory, but the expected yield of such detailed spectra is low.

Significant additions of spectral lines could also arise from the instances in which a meteor of asteroidal origin is photographed with a spectrograph. These are very rare events, and scarcely account for one per cent of the existing meteor spectra of the world.

The author wishes to express his thanks to the entire observing staff of the meteor observatories in Alberta for their persistence and enthusiasm, often under difficult observing conditions, and to Dr. P. M. Millman for valuable discussions concerning spectral identifications.

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