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9. Spectral Analysis of Four Meteors

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Four meteor spectra from the NASA LRC Faint Meteor Spectra Patrol are analyzed for chemical composition and radiative processes. The chemical compositions of the Taurid, Geminid, and Perseid meteors were found to be similar to that of a typical stony meteorite. The chemical composition of the sporadic meteor was found to be similar to that of a nickel-iron meteorite. The radiation from optical meteors (+1 to −10 absolute photographic magnitude) was found to be similar to that of a low-temperature gas, except that strong, anomalous ionic radiation is superposed on the neutral radiation in bright (< −3 mag), fast meteors.

DURING THE 1960s, THE ACTIVITY IN SPACE resulted in a strong effort directed toward determining the meteoroid environment and its attendant hazard to spacecraft. By 1971, lack of definitive meteoroid damage to spacecraft had shown that the meteoroid environment did not present a significant danger to most missions. At the same time, the measured uncertainties in the mass flux of meteoroids, over a wide range of mass, had been reduced from orders of magnitude to factors of 3 to 10 (Ayres et al., 1970; Cook et al., 1963; D'Aiutolo et al., 1967; Harvey, 1970). However, the multitude of observations (Grygar et al., 1968; Harvey, 1971a; Lindblad, 1963; Millman, 1967) during this time period clearly indicated that meteoroids were very heterogeneous in nature and that the simplified concept of a mass-flux representation of the meteoroid environment had limitations. By 1970, the statistical or gross meteoroid environment was fairly well determined. However, many of the techniques that are applied to the study of the overall environment are not well suited to a refined study of individual meteoroids.

Meteor spectra research being conducted by NASA Langley Research Center is intended as a detailed study of individual meteoroids. This research is based on the techniques and principles of quantitative spectroscopy. The data for this research are obtained from the NASA LRC Faint Meteor Spectra Patrol (Harvey, 1971a). This patrol provides statistical quantities (several hundred per year) of meteor spectra. These spectra are used for detailed measurements of composition, for statistical studies of composition, and for study of meteor radiation.

This paper presents the results of the detailed analysis of four of the better (>100 lines) meteor spectra obtained from the patrol. The approach used in these analyses is to measure the population of excited states of the meteoric gas, and to use the parameter obtained from these measurements to obtain quantitative elemental chemical composition of the initial meteoroid. Meteor radiation processes are discussed. The "effective radiation temperatures" and "derived meteoroid compositions" are presented. Prior to this present effort only three meteor spectra are known to have been quantitatively analyzed for composition (Ceplecha, 1964, 1965; Harvey, 1970).

The NASA LRC Faint Meteor Spectra Patrol (Harvey, 1971a) has been obtaining meteor spectra since November 1968. The patrol uses specially designed Maksutov slitless spectrographs and a photoelectric meteor-detection-shutter system. By the end of 1970, approximately 500 meteor spectra had been obtained by the patrol. Four of these were selected as useful for detailed spectroscopic analysis and as generally representative of the brighter meteors that had been photographed. Further, the meteoroids that produced these four spectra are also generally representative of the meteor velocity range. One of the spectra is of a slow sporadic meteor. The other three spectra are of Taurid, Geminid, and Perseid meteors, respectively.

SPORADIC METEOR

The spectrum of the slow, sporadic meteor is shown in figure 1. This spectrum was recorded during the night of April 4, 1969, and no position or orbital data are available. A velocity of 20 km/s or less is estimated for the meteor on the basis of a lower "effective radiation temperature" measurement than that obtained for the 28 km/s Taurid. The meteor spectrum was photographed with a 150-mm aperture, $f/1.3$ Maksutov slitless spectrograph equipped with a 407 line/mm diffraction grating. Typical slow-meteor values of 90 km initial height, trajectory-optical axis angle of 45°, and a duration of 2 s, were used to compute the intensity of this meteor. By comparing the computed intensity of this meteor in the blue and near ultraviolet region with that of an artificial meteor (Harvey, 1967a), an absolute photographic magnitude brighter than -10 is obtained for the meteor. As can be seen in figure 1, this bright meteor was recorded in the third, fourth, and fifth orders of the spectrum with dispersions of 40, 32, and 24 Å/mm, respectively. One hundred and twenty-two of the strongest lines at point A in the spectrum have been identified in a preliminary wavelength analysis and are listed in table 1. The first column of table 1 lists the wavelengths measured from the microdensitometer tracing, column two lists the identified wavelengths (Corliss and Bozman, 1962; Moore, 1945), column three lists the multiplet numbers from Moore (1945), column four lists the statistical weight-Einstein transition probability products from Corliss and Bozman (1962). Columns five and six list the upper and lower energy levels of the atomic transitions as listed in Moore (1945). Most of the lines are from ground state multiplets of iron. The large number of lines and the good spectral resolution lend themselves to a detailed analysis. The spectrum was recorded on a blue sensitive emulsion and covers the wavelength interval of 3100 Å to 4600 Å in partially overlapping orders.

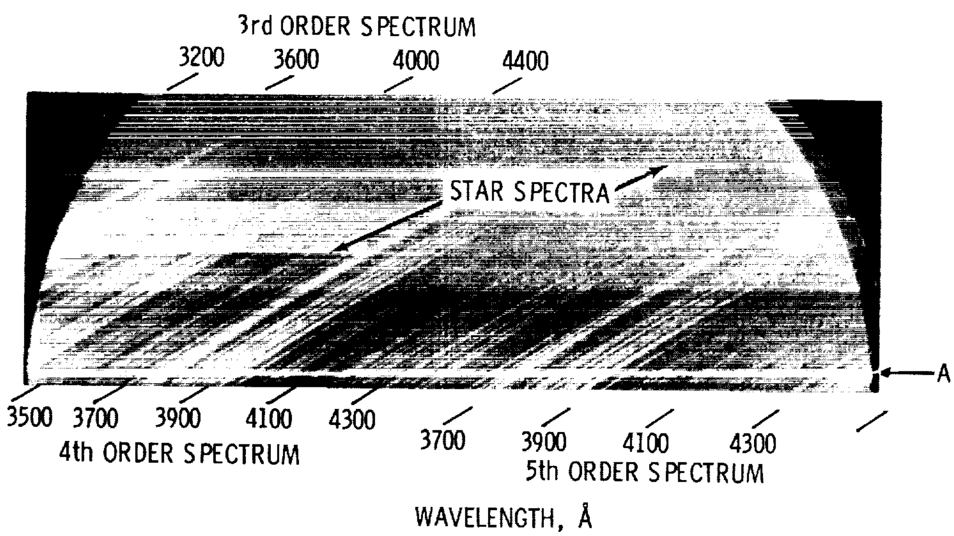

FIGURE 1.—Enlargement of spectrogram of a sporadic meteor.

TABLE 1.—*Wavelength Identifications of Sporadic Meteor*

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3424.8	3424.29	81 Fe	17	2.17	5.77
3426.5	3426.39	82 Fe	7.4	2.17	5.77
	3426.64	82 Fe	7.7	2.19	5.79
	3427.12	81 Fe	34	2.17	5.77
3429.0	3428.20	81 Fe	8.8	2.19	5.79
3433.0	3433.04	23 Co	9.1	0.63	4.22
	3433.60	52 Cr	44	2.53	6.13
3436.5	3436.19	52 Cr	26	2.53	6.13
3440.6	3440.61	6 Fe	2.8	0.00	3.59
	3440.99	6 Fe	0.64	0.05	3.64
3444.0	3443.88	6 Fe	0.34	0.09	3.67
3446.0	3445.15	81 Fe	17	2.19	5.77
	3446.26	20 Ni	3.8	0.11	3.69
3447.5	3447.28	82 Fe	5.3	2.19	5.77
3450.5	3450.33	82 Fe	8.9	2.21	5.79
3452.5	3452.28	25 Fe	0.49	0.95	4.53
	3452.89	17 Ni	1.0	0.11	3.68
3461.9	3461.65	17 Ni	3.2	0.03	3.59
3466.0	3465.86	6 Fe	0.52	0.11	3.67
3472.0	3471.27	82 Fe		2.21	5.77
	3472.54	20 Ni	1.2	0.11	3.66
3475.5	3475.45	6 Fe	0.64	0.09	3.64
3476.5	3476.70	6 Fe	0.28	0.12	3.67
3482.5	3483.01	24 Fe		0.91	4.45
3490.6	3490.58	6 Fe	0.58	0.05	3.59
3492.2	3492.96	18 Ni	3.9	0.11	3.64
3497.8	3497.84	6 Fe	0.19	0.11	3.64
3501.7	3502.28	21 Co	11	0.43	3.95
3505.0	3506.31	21 Co	9.4	0.51	4.03
3512.5	3512.64	21 Co	7.4	0.58	4.09
3514.0	3513.82	24 Fe	1.7	0.86	4.37
3514.8	3515.05	19 Ni	4.5	0.11	3.62
3522.0	3521.26	24 Fe	1.7	0.91	4.42
3526.0	3524.54	18 Ni	4.6	0.03	3.53
	3526.04	6 Fe	0.13	0.09	3.59
3557.5	3558.52	24 Fe	3.5	0.99	4.45
3566.0	3565.38	24 Fe	7.8	0.95	4.42
	3566.37	36 Ni	6.4	0.42	3.88
3569.5	3570.10	24 Fe	18	0.91	4.37
3578.5	3578.69	4 Cr	8.3	0.00	3.45
3581.2	3581.20	23 Fe	23	0.86	4.30
3585.5	3585.32	23 Fe	1.7	0.95	4.40
	3585.71	23 Fe	1.3	0.91	4.35
3586.8	3586.99	23 Fe	2.0	0.99	4.43
3589.6	3589.11	23 Fe	0.26	0.86	4.29
3593.2	3593.49	4 Cr	7.0	0.00	3.43
3605.5	3605.33	4 Cr	5.2	0.00	3.42
	3605.46	294 Fe	51	2.72	6.14
3606.7	3606.68	294 Fe	65	2.68	6.10
3608.9	3608.86	23 Fe	10	1.01	4.43
3618.8	3618.77	23 Fe	9.5	0.99	4.40
3631.5	3631.46	23 Fe	8.6	0.95	4.35
3647.8	3647.84	23 Fe	6.1	0.91	4.29

TABLE 1.—*Wavelength Identifications of Sporadic Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3649.5	3649.30	5 Fe	~.025	0.00	3.38
3680.0	3679.92	5 Fe	0.29	0.00	3.35
3683.0	3683.06	5 Fe	0.055	0.05	3.40
3687.5	3687.46	21 Fe	2.5	0.86	4.20
3705.3	3705.57	5 Fe	0.38	0.05	3.38
3708.0	3707.82	5 Fe	0.14	0.09	3.42
3709.0	3709.25	21 Fe	2.9	0.91	4.24
3717.0	3716.45	388 Fe	15	2.93	6.25
3720.2	3719.94	5 Fe	2.5	0.00	3.32
3722.0	3722.56	5 Fe	0.40	0.09	3.40
3725.0	3724.38	124 Fe	5.9	2.27	5.58
3727.0	3726.92	385 Fe	8.7	3.03	6.34
3735.0	3734.87	21 Fe	20	0.86	4.16
3737.3	3737.13	5 Fe	1.5	0.05	3.35
3743.0	3743.36	21 Fe	2.3	0.99	4.28
3746.0	3745.56	5 Fe	1.2	0.09	3.38
3749.0	3749.49	21 Fe	13	0.91	4.20
3758.5	3758.24	21 Fe	10	0.95	4.24
3761.0	3760.05	177 Fe	5.5	2.39	5.68
	3760.53	76 Fe	0.97	2.21	5.49
3764.0	3763.79	21 Fe	6.2	0.99	4.26
3787.0	3786.68	22 Fe	0.11	1.01	4.27
3788.0	3787.88	21 Fe	1.7	1.01	4.26
3790.5	3790.10	22 Fe	0.21	0.99	4.24
3796.0	3795.00	21 Fe	2.3	0.99	4.24
3799.5	3797.52	607 Fe	21	3.22	6.47
	3798.51	21 Fe	.93	0.91	4.16
	3799.55	21 Fe	1.5	0.95	4.20
3815.84	3815.84	45 Fe	16	1.48	4.71
3821.5	3820.43	20 Fe	12	0.86	4.09
3825.0	3824.44	4 Fe	0.28	0.00	3.23
	3825.88	20 Fe	8.9	0.91	4.14
3829.5	3829.35	3 Mg	11	2.70	5.92
3830.2	3832.51	3 Mg	23	2.70	5.92
3834.0	3834.22	20 Fe	3.9	0.95	4.17
3838.3	3838.26	3 Mg	39	2.70	5.92
3840.7	3840.44	20 Fe	2.6	0.99	4.20
3850.5	3849.97	20 Fe	1.7	1.01	4.21
3857.2	3856.37	4 Fe	0.31	0.05	3.25
3860.0	3859.91	4 Fe	1.4	0.00	3.20
3865.0	3865.53	20 Fe	1.1	1.01	4.20
3879.0	3878.02	20 Fe	1.4	0.95	4.14
	3878.58	4 Fe	0.33	0.09	3.27
3887.0	3886.28	4 Fe	0.63	0.05	3.23
3897.0	3895.66	4 Fe	0.14	0.11	3.28
3900.5	3899.71	4 Fe	0.21	0.09	3.25
3903.5	3903.90	429 Fe	4.2	2.98	6.14
3905.5	3905.53	3 Si	0.86	1.90	5.06
3906.5	3906.48	4 Fe	0.055	0.11	3.27
3923.1	3922.91	4 Fe	0.18	0.05	3.20
3928.0	3927.92	4 Fe	0.26	0.11	3.25
3930.5	3930.30	4 Fe	0.27	0.09	3.23
3933.5	3933.67	1 Ca II	0.91	0.00	3.14

TABLE 1.—*Wavelength Identifications of Sporadic Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3942.2	3942.44	364 Fe	2.5	2.83	5.96
3969.3	3968.47	1 Ca II	0.45	0.00	3.11
	3969.26	43 Fe	4.4	1.48	4.59
4004.5	4005.25	43 Fe	3.6	1.55	4.63
4031.0	4030.76	2 Mn	1.4	0.00	3.06
4033.0	4033.07	2 Mn	0.95	0.00	3.06
4036.0	4034.49	2 Mn	0.54	0.00	3.06
4045.8	4045.82	43 Fe	22	1.48	4.53
4063.5	4063.60	43 Fe	9.9	1.55	4.59
4071.5	4071.74	43 Fe	9.1	1.60	4.63
4133.0	4132.06	43 Fe	2.7	1.60	4.59
4143.9	4143.42	523 Fe	16	3.03	6.01
	4143.87	43 Fe	2.9	1.55	4.53
4202.0	4202.03	42 Fe	2.0	1.48	4.42
4206.0	4206.70	3 Fe		0.05	2.99
4216.0	4216.19	3 Fe	0.0031	0.00	2.93
4226.5	4226.73	2 Ca	1	0.00	2.92
4251.0	4250.79	42 Fe	1.5	1.55	4.45
4254.5	4254.35	1 Cr	2.0	0.00	2.90
4257.8	4258.32	3 Fe		0.09	2.99
4271.8	4271.76	42 Fe	5.2	1.48	4.37
4274.5	4274.80	1 Cr	1.5	0.00	2.89
4290.0	4289.72	1 Cr	0.95	0.00	2.88
4291.5	4291.66	3 Fe		0.09	2.99
4293.5	4294.13	41 Fe	0.71	1.48	4.35
4299.0	4299.24	152 Fe	5.2	2.41	5.29
4308.0	4307.91	42 Fe	5.9	1.55	4.42
4325.8	4325.76	42 Fe	6.1	1.60	4.45
4376.0	4375.93	2 Fe	0.0094	0.00	2.82
4383.5	4383.55	41 Fe	7.7	1.48	4.29
4404.75	4404.75	41 Fe	4.4	1.55	4.35
4427.3	4427.31	2 Fe	0.0091	0.05	2.84
4461.65	4461.65	2 Fe	0.0052	0.09	2.85
4482.17	4482.17	2 Fe	0.0053	0.11	2.86

TAURID METEOR

The spectrum of the Taurid meteor is shown in figure 2. This spectrum was obtained during the night of November 4, 1969. The meteor occurred at 22:25 hours, local time. A beginning height of 100 km was assumed for the meteor. This height is in general agreement with beginning heights of meteors of similar brightness and velocity (Jacchia et al., 1967). A terminal height of 68 km was calculated from the beginning height and relevant geometry. The meteor began 8° from the radiant, and the trajectory made an angle of 10° with the optical axis of the spectrograph. Hence the meteor was nearly "head-on" and was very favorable for photographic recording. An absolute meteor magnitude of −4 was obtained for this meteor by comparing its intensity in the blue and near ultraviolet region with that of an artificial meteor (Harvey, 1967a). The Taurid meteor spectrum was recorded on the same spectrograph as the sporadic meteor spectrum. However, the Taurid spectrum (as well as the Geminid and Perseid spectra) were recorded on "meteor recording film SO-153," which is similar to extended red emulsion type 2485. That is, the spectrum covers the wavelength interval 3100 Å to 7000 Å. Two hundred

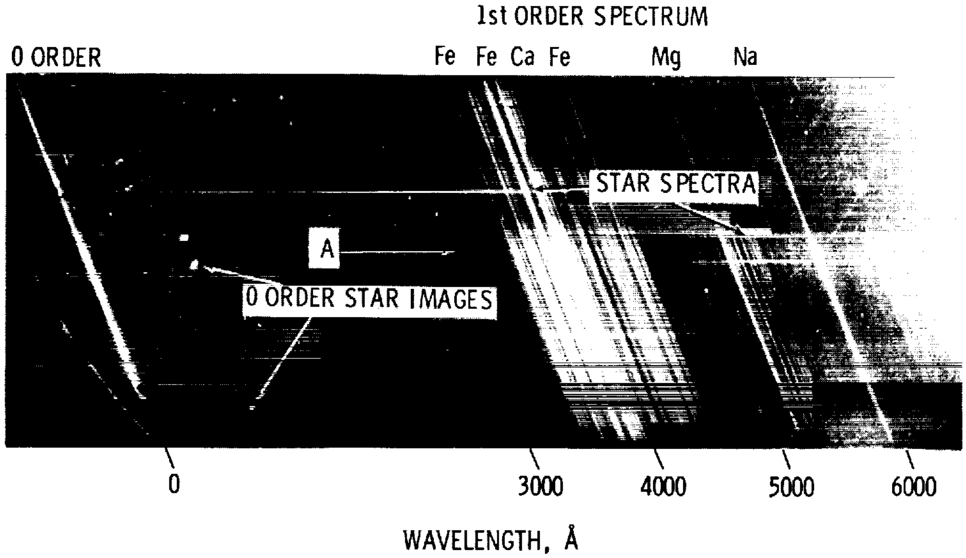

FIGURE 2.—Enlargement of a spectrogram of a Taurid meteor.

and thirty-seven of the strongest lines at position A in the spectrum have been identified and are listed in table 2. The strongest features in the spectrum are multiplets 4, 5, and 20 of neutral iron, 2 of neutral magnesium, and the sodium D lines. The spectrum suffers from mutliple zero-order star images and a dense and nonuniform background.

GEMINID METEOR

The spectrum of the Geminid meteor is shown in figure 3. This spectrum was obtained on the night of December 12, 1969. The meteor occurred at approximately 03:40, local time. The meteor began 51° from the Geminid radiant and ended 63° from the radiant. An estimated beginning height of 100 km was again used from which a terminal height of 68 km was computed. An absolute meteor magnitude of −5 was obtained for this meteor by the same method used for the Taurid. The Geminid spectrum was recorded by the same spectrograph as the Taurid spectrum. One hundred and fifty-seven of the strongest lines at position A have been identified in the preliminary wavelength analysis and are listed in table 3. The strongest features in the spectrum are multiplets 4, 5, and 20 of neutral iron, 2 of magnesium, and the sodium D lines. This Geminid spectrum is a "clean" spectrum in that it is not degraded by star images, poor resolution, or nonuniform background.

PERSEID METEOR

The spectrum of the Perseid meteor is shown in figure 4. The spectrum was obtained on the night of August 12, 1969. The meteor occurred between 02:30 and 4:00, local time. The meteor was approximately 90° from the radiant and traveling nearly perpendicular to the optical axis of the spectrograph when photographed. A beginning height of 105 km was obtained from the maximum of the auroral green line. A terminal height of 92 km was calculated. A maximum brightness of −9 absolute meteor magnitude was obtained for this Perseid meteor by the same method as used for the Taurid and Geminid meteors. This spectrum was also recorded on the same spectrograph which recorded the other three spectra. As can be seen in figure 4, the upper third of the spectrum is similar to that of the Geminid and Taurid meteors. However, in the latter part of the spectrum, the ionic lines of calcium, magnesium, and silicon become dominant. Ninety-four of the strongest lines at position A have been identified in the preliminary wavelength analysis and are listed in table 4. The entries of table 4 are from the same source as tables 1 to 3 except that the gA values for Si

TABLE 2.—*Wavelength Identifications of Taurid Meteor*

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3098	3099.97	28 Fe	8.6	0.91	4.89
	3100.30	28 Fe	3.9	0.99	4.97
	3100.67	28 Fe	3.6	0.95	4.93
	3101.55	25 Ni	4.6	0.11	4.09
3135	3134.11	25 Ni	5.8	0.21	4.15
3184	3184.90	7 Fe	0.086	0.05	3.93
3193	3191.66	8 Fe	0.087	0.00	3.87
	3193.21	7 Fe	0.14	0.00	3.86
3200	3199.92	27 Ti	14	0.05	3.90
3214	3214.40	7 Fe	0.086	0.09	3.93
3224	3225.79	155 Fe	107	2.39	6.21
3233	3234.52	2 Ti II	16	0.05	3.86
3244	3243.06	22 Ni	0.62	0.03	3.83
3251	3251.24	93 Fe		2.19	5.98
3254	3254.36	620 Fe		3.25	7.05
3265	3265.62	91 Fe	18	2.17	5.95
3270	3271.00	91 Fe	22	2.19	5.96
3284	3284.59	91 Fe		2.19	5.95
3291	3290.99	95 Fe		2.21	5.96
	3292.59	91 Fe		2.21	5.96
3301	3302.32	2 Na	0.65	0.00	3.74
	3302.99	2 Na	0.33	0.00	3.74
3306	3306.0	91 Fe	38	2.91	5.92
	3306.4	91 Fe	40	2.21	5.95
3320	3320.26	9 Ni	0.39	0.16	3.88
3332	3331.62	191 Fe		2.42	6.13
3335	3334.22	190 Fe		2.42	6.12
3342	3341.88	24 Ti	13	0.00	3.69
3352	3344.51	11 Ca		1.88	5.56
	3350.21	11 Ca		1.88	5.56
	3350.36	11 Ca		1.88	5.56
	3354.64	24 Ti	9.7	0.02	3.71
3363	3361.92	11 Ca		1.89	5.56
	3362.13	11 Ca		1.89	5.56
3365	3365.77	38 Ni	0.63	0.42	4.09
	3366.17	8 Ni	0.35	0.16	3.83
3375	3374.22	17 Ni	0.20	0.03	3.68
3384	3383.69	85 Fe		2.19	5.84
	3383.98	83 Fe	9.1	2.17	5.81
3399	3399.34	85 Fe	25	2.19	5.82
3404	3404.36	83 Fe	17	2.19	5.81
3407	3407.46	83 Fe	33	2.17	5.79
3414	3413.14	85 Fe	26	2.19	5.80
3424	3424.29	81 Fe	17	2.17	5.77
3425	3426.39	82 Fe	7.4	2.19	5.79
	3426.64	82 Fe	7.7	2.19	5.79
3429	3427.12	81 Fe	34	2.17	5.77
3440	3440.61	6 Fe	2.8	0.00	3.59
	3440.99	6 Fe	0.64	0.05	3.64
3450	3450.33	82 Fe	8.9	2.21	5.79
	3451.92	81 Fe	8.8	2.21	5.79
3460	3458.47	19 Ni	4.9	0.21	3.78
3462	3461.65	17 Ni	3.2	0.03	3.59

TABLE 2.—*Wavelength Identifications of Taurid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3466	3465.86	6 Fe	0.52	0.11	3.67
3476	3475.45	6 Fe	0.64	0.09	3.64
3491	3490.58	6 Fe	0.58	0.05	3.59
	3492.96	18 Ni	3.9	0.11	3.64
3499	3497.84	6 Fe	0.19	0.11	3.64
3514	3513.82	24 Fe	1.7	0.86	4.37
3526	3526.04	6 Fe	0.13	0.09	3.59
3534	3536.56	326 Fe	56	2.86	6.35
3541	3541.09	326 Fe	65	2.84	6.32
	3542.08	326 Fe	61	2.85	6.34
3554	3554.93	326 Fe	73	2.82	6.29
3560	3558.52	24 Fe	3.5	0.99	4.45
3565	3565.38	24 Fe	7.8	0.95	4.42
3570	3570.10	24 Fe	18	0.91	4.37
3578	3578.69	4 Cr	8.3	0.00	3.45
3581	3581.20	23 Fe	23	0.86	4.30
3586	3586.99	23 Fe	2.0	0.99	4.43
3588	3589.11	23 Fe	0.26	0.86	4.29
3594	3594.64	322 Fe	21	2.84	6.27
3604	3603.21	295 Fe	33	2.68	6.11
	3605.46	294 Fe	33	2.72	6.14
3607	3606.68	294 Fe	65	2.68	6.10
3609	3608.86	23 Fe	10	1.01	4.43
3611	3610.16	321 Fe	48	2.80	6.21
3619	3618.77	23 Fe	9.5	0.99	4.40
3620	3619.39	35 Ni	7.5	0.42	3.83
3632	3631.46	23 Fe	8.6	0.95	4.35
	3632.04	496 Fe	26	3.06	6.46
3639	3638.30	294 Fe	28	2.75	6.14
3646	3645.82	496 Fe	20	3.10	6.48
3648	3647.84	23 Fe	6.1	0.91	4.29
3659	3659.52	180 Fe	9.9	2.44	5.82
3671	3669.52	291 Fe	32	2.72	6.08
3680	3679.92	5 Fe	0.29	0.00	3.35
3683	3683.06	5 Fe	0.055	0.05	3.40
3687	3687.46	21 Fe	2.5	0.86	4.20
3694	3794.01	394 Fe	72	3.03	6.37
3700	3701.09	385 Fe	85	2.99	6.32
3706	3705.57	5 Fe	0.38	0.05	3.38
3708	3707.82	5 Fe	0.14	0.09	3.42
3720	3719.94	5 Fe	2.5	0.00	3.32
3723	3722.56	5 Fe	0.40	0.09	3.40
3733	3733.32	5 Fe	0.36	0.11	3.42
	3634.87	21 Fe	20	0.86	4.16
3737	3737.13	5 Fe	1.5	0.05	3.35
3747	3745.56	5 Fe	1.2	0.09	3.38
	3745.90	5 Fe	0.31	0.12	3.42
3749	3748.26	5 Fe	0.71	0.11	3.40
	3749.49	21 Fe	13	0.91	4.20
3759	3758.24	21 Fe	10	0.95	4.24
3764	3763.79	21 Fe	6.2	0.99	4.26
	3765.54	608 Fe	50	3.22	6.50
3768	3767.19	21 Fe	4.6	1.01	4.28

TABLE 2.—*Wavelength Identifications of Taurid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3775	3774.82	73 Fe	0.59	2.21	5.48
	3775.57	33 Ni	0.57	0.42	3.69
	3776.45	74 Fe	0.53	2.17	5.43
3786	3786.68	22 Fe		1.01	4.27
3791	3790.10	22 Fe	0.21	0.99	4.24
3795	3795.00	21 Fe	2.3	0.99	4.24
3797	3798.51	21 Fe	0.93	0.91	4.16
	3799.55	21 Fe	1.5	0.95	4.20
3813	3812.96	22 Fe	1.0	0.95	4.19
3817	3815.84	45 Fe	16	1.48	4.71
3821	3820.43	20 Fe	12	0.86	4.09
3825	3824.44	4 Fe	0.28	0.00	3.32
	3825.88	20 Fe	8.9	0.91	4.14
3831	3827.82	45 Fe	15	1.55	4.77
	3829.35	3 Mg	11	2.70	5.92
	3832.51	3 Mg	23	2.70	5.92
3838	3838.26	3 Mg	39	2.70	5.92
3849	3849.97	20 Fe	1.7	1.01	4.21
	3850.82	22 Fe	0.22	0.99	4.19
3855	3856.37	4 Fe	0.31	0.05	3.25
	3856.37	1 Si II		6.83	10.03
3860	3859.91	4 Fe	1.4	0.00	3.20
3862	3862.59	1 Si II		6.83	10.03
3874	3873.76	175 Fe	2.8	2.42	5.61
3878	3878.02	20 Fe	1.4	0.95	4.14
	3878.58	4 Fe	0.33	0.09	3.27
3886	3886.28	4 Fe	0.63	0.05	3.23
3896	3895.66	4 Fe	0.14	0.11	3.28
3900	3899.71	4 Fe	0.21	0.09	3.25
3905	3905.53	3 Si	0.20	1.90	5.06
	3906.48	4 Fe	0.055	0.11	3.27
3921	3920.26	4 Fe	0.14	0.12	3.27
3922	3922.91	4 Fe	0.18	0.05	3.20
3929	3927.92	4 Fe	0.26	0.11	3.25
	3930.30	4 Fe	0.27	0.09	3.23
3936	3935.82	362 Fe	3.5	2.82	5.96
3940	3940.88	20 Fe	0.041	0.95	4.09
3944	3944.03	1 Al	0.66	0.00	3.13
3956	3956.68	278 Fe	9.1	2.68	5.80
3969.3	3969.26	43 Fe	4.4	1.48	4.59
4000	3997.40	278 Fe	11	2.72	5.80
	3998.06	276 Fe	3.7	2.68	5.77
4005	4005.25	43 Fe	3.6	1.55	4.63
4010	4009.72	72 Fe	1.4	2.21	5.29
4030	4030.76	2 Mn	1.4	0.00	3.06
	4033.07	2 Mn	0.95	0.00	3.06
	4034.49	2 Mn	0.54	0.00	3.06
4040	4041.36	5 Mn	34	2.11	5.16
4045	4045.82	43 Fe	22	1.48	4.53
4060	4058.93	5 Mn	7.4	2.17	5.21
4063	4063.60	43 Fe	9.9	1.55	4.59
4071	4071.74	43 Fe	9.1	1.60	4.63
4082	4082.94	5 Mn	7.1	2.17	5.19

TABLE 2.—*Wavelength Identifications of Taurid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	*gA* ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
	4083.63	5 Mn	6.9	2.15	5.18
4100	4100.75	18 Fe		0.86	3.86
4108	4107.49	354 Fe	5.6	2.82	5.82
4120	4118.55	801 Fe	33	3.56	6.55
4132	4132.06	43 Fe	2.7	1.60	4.59
4140	4139.93	18 Fe		0.99	3.97
	4143.87	43 Fr	2.9	1.55	4.53
4155	4154.50	355 Fe	5.3	2.82	5.79
	4156.80	354 Fe	5.3	2.82	5.79
4172	4172.75	19 Fe		0.95	3.91
4178	4177.60	18 Fe		0.91	3.86
4189	4187.04	152 Fe	6.9	2.44	5.39
	4187.80	152 Fe	6.5	2.41	5.36
4201	4202.03	42 Fe	2.0	1.48	4.42
4206	4206.70	3 Fe		0.05	2.99
4215	4216.19	3 Fe	0.0031	0.00	2.93
4226.7	4226.73	2 Ca	1	0.00	2.92
4235	4235.94	152 Fe	7.9	2.41	5.33
4240	4238.82	693 Fe	9.4	3.38	6.29
4251	4250.79	42 Fe	1.5	1.55	4.45
4253	4254.35	1 Cr	2.0	0.00	5.36
4261	4260.48	152 Fe	15	2.39	5.29
4272	4271.76	42 Fe	5.2	1.48	4.37
4276	4274.80	1 Cr	1.5	0.00	2.89
4283	4282.41	71 Fe	2.0	2.17	5.05
4291	4289.72	1 Cr	0.95	0.00	2.88
	4291.47	3 Fe		0.09	2.99
4300	4299.24	152 Fe	5.2	2.41	5.29
4308	4307.91	42 Fe	5.9	1.55	4.42
4325	4325.76	42 Fe	6.1	1.60	4.45
4338	4337.05	42 Fe	0.23	1.55	4.40
4354	4352.74	71 Fe	1	2.21	5.05
4368	4368.30	5 O		9.48	12.31
4376	4375.93	2 Fe	0.0094	0.00	2.82
4383	4383.55	41 Fe	7.7	1.48	4.29
4405	4404.75	41 Fe	4.4	1.55	4.35
4416	4415.12	41 Fe	2.8	1.60	4.40
4427	4427.31	2 Fe	0.0099	0.05	2.84
4454	4454.78	4 Ca	7.5	1.89	4.66
	4455.89	4 Ca	0.97	1.89	4.66
4462	4461.65	2 Fe	0.0052	0.09	2.85
	4462.05	28 Mn	16	3.06	5.83
4482	4482.17	2 Fe	0.0053	0.11	2.86
4489	4489.74	2 Fe		0.12	2.87
4496	4494.57	68 Fe	1.2	2.19	4.93
4529	4528.62	68 Fe	1.8	2.17	4.89
	4531.15	39 Fe	0.076	1.48	4.20
4570	4571.10	1 Mg		0.00	2.70
4581	4581.40	23 Ca	0.96	2.51	5.21
4586	4585.87	23 Ca	1.5	2.51	5.21
4601	4602.94	39 Fe	0.088	1.48	4.16
4692	4691.41	409 Fe		2.98	5.61
4703	4702.98	11 Mg		4.33	6.95

TABLE 2.—*Wavelength Identifications of Taurid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
4737	4736.78	554 Fe	2.5	3.20	5.80
4761	4761.53	21 Mn		2.94	5.53
	4762.38	21 Mn	12	2.88	5.47
4768	4765.86	21 Mn		2.93	5.52
	4766.43	21 Mn	8.4	2.91	5.50
4825	4823.52	16 Mn	4.0	2.31	4.87
4861	4859.75	318 Fe	1.3	2.86	5.40
4872	4871.32	318 Fe	3.7	2.85	5.39
	4872.15	318 Fe	2.2	2.87	5.40
4878	4878.22	318 Fe	0.77	2.87	5.40
4892	4890.77	318 Fe	2.2	2.86	5.39
	4891.50	318 Fe	4.7	2.84	5.36
4905	4903.32	318 Fe	0.62	2.87	5.39
4919	4919.00	318 Fe	2.9	2.85	5.36
4920	4920.50	318 Fe	6.5	2.82	5.33
4939	4938.82	318 Fe		2.86	5.36
4958	4957.31	318 Fe	2.2	2.84	5.33
	4957.61	318 Fe	6.4	2.80	5.29
4967	4966.10	687 Fe		3.32	5.80
4988	4985.55	318 Fe		2.85	5.33
4995	4994.13	16 Fe		0.91	3.38
5006	5006.13	318 Fe	1.3	2.82	5.29
5014	5012.07	16 Fe	0.0067	0.86	3.32
5041	5041.76	36 Fe	0.023	1.48	3.93
5054	5051.54	16 Fe	0.0061	0.91	3.35
5070	5068.79	383 Fe	0.60	2.93	5.36
5081	5083.34	16 Fe	0.0052	0.95	3.38
5110	5110.41	1 Fe	0.0014	0.00	2.41
5125	5123.72	16 Fe		1.01	3.42
5133	5133.68	1092 Fe	13	4.16	6.56
5138	5139.26	383 Fe	1.6	2.99	5.39
	5139.48	383 Fe	2.0	2.93	5.33
5152	5153.40	8 Na	0.38	2.10	4.49
5170	5166.29	1 Fe		0.00	2.39
	5167.34	2 Mg	1.2	2.70	5.09
	5167.49	37 Fe		1.55	3.91
	5168.90	1 Fe		0.05	2.44
	5171.60	36 Fe		1.48	3.86
	5172.70	2 Mg	3.5	2.70	5.09
5184	5183.62	2 Mg	6.4	2.70	5.09
5207	5204.58	1 Fe		0.09	2.46
5218	5216.28	36 Fe	0.064	1.60	3.97
5227	5227.19	37 Fe	0.27	1.55	3.91
5244	5241.76	36 Fe		1.48	3.93
5250	5250.65	66 Fe		2.19	4.54
5261	5263.33	553 Fe		3.25	5.60
5270	5269.54	15 Fe	0.098	0.86	3.20
	5270.36	37 Fe	0.20	1.60	3.94
5281	5281.80	383 Fe	1.3	3.03	5.36
	5283.63	553 Fe		3.23	5.56
5328	5328.05	15 Fe	0.087	0.91	3.23
5340	5341.03	37 Fe	0.042	1.60	3.91
	5341.06	4 Mn	0.26	2.11	4.42
5371	5371.49	15 Fe	0.062	0.95	3.25

TABLE 2.—*Wavelength Identifications of Taurid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^{8}$/s)	E_1 (eV)	E_2 (eV)
5397	5397.13	15 Fe	0.032	0.91	3.20
5403	5405.78	15 Fe	0.038	0.99	3.27
5423	5420.36	4 Mn	0.14	2.13	4.49
5429	5429.70	15 Fe	0.039	0.95	3.23
5445	5446.92	15 Fe	0.031	0.99	3.25
5454	5455.61	15 Fe	0.022	1.01	3.27
5472	5470.64	4 Mn	0.10	2.15	4.41
5497	5497.52	15 Fe	0.0084	1.01	3.25
5507	5506.78	15 Fe	0.0100	0.99	3.23
5528	5528.46	9 Mg	1.6	4.33	6.56
5569	5569.62	686 Fe	2.4	3.40	5.62
5574	5572.85	686 Fe	3.4	3.38	5.60
5580	5581.97	21 Ca		2.51	4.72
5585	5586.76	686 Fe	4.2	3.35	5.56
5591	5588.76	21 Ca		2.51	4.72
	5594.47	21 Ca		2.51	4.72
5602	5601.48	21 Ca		2.51	4.72
	5602.85	21 Ca		2.51	4.72
	5602.96	686 Fe	0.96	3.42	5.62
5614	5615.65	686 Fe	4.7	3.32	5.52
5660	5658.54	686 Fe		3.38	5.56
5690	5688.22	6 Na	1.8	2.10	4.27
5710	5708.44	10 Si		4.93	7.09
5772	5772.26	17 Si		5.06	7.20
5790	5789.8	FeO B			
5798	5797.91	9 Si		4.93	7.06
5859	5857.46	47 Ca	3.6	2.92	5.03
5891	5889.95	1 Na	1.8	0.00	2.10
5894	5895.92	1 Na	0.90	0.00	2.09
5946	5948.58	16 Si		5.06	7.14
6155	6154.11	5 Na		2.10	4.10
6217	6218.9	FeO A			
6347	6347.09	2 Si II		8.09	10.03
6439	6439.07	18 Ca		2.51	4.43

II were computed from the absorption oscillator strengths of Griem (1964). A large number of features in the 3100 Å to 3600 Å region remain unidentified. This spectrum suffers greatly from multiple zero-order star images and poor imagery.

DATA REDUCTION

The data reduction of the meteor spectrograms consisted of two parts: the wavelength identifications, and the absolute spectral photometry. The method used for the wavelength reductions was to obtain 40× densitometer tracings of the spectra. Wavelength scales were then constructed and positioned according to the known wavelengths of strong lines in the spectra. The wavelengths of the meteor radiation were read directly from the constructed scale. These wavelengths were read to the nearest angstrom. This method allows convenient checking of wavelength and relative intensity of lines during identification. Numerous sources were used in checking the wavelengths of the identified lines. The primary ones were Ceplecha (1964), Halliday (1961, 1969), Harvey (1967a) and Moore (1945). The identifications in the 3100 Å to 3600 Å region were particularly difficult, and many features have remained unidentified. The wavelengths

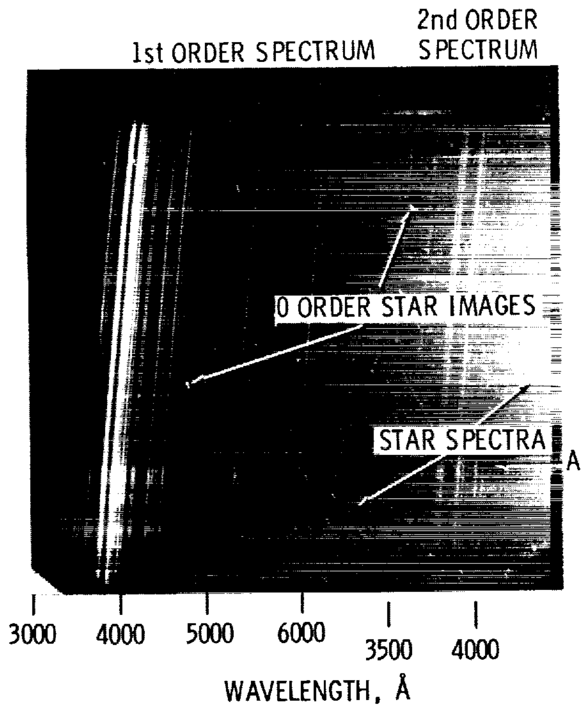

FIGURE 3.—Enlargement of a spectrogram of a Geminid meteor.

and identifications of features in the four spectra are listed in tables 1 to 4.

The spectral photometry used in the data reduction follows closely that of Harvey (1967b). This photometry is based on calibration of the meteor irradiance with the irradiance from a quartz-iodine lamp that is a standard of spectral irradiance. Again the 3100 Å to 3600 Å spectral region has proven to be difficult to work in because of the relatively low energy of the standard lamp and the high atmospheric attenuation in this region.

As mentioned in the data section, assumed heights and shower velocities were used for the three shower meteors. Factors which have further degraded the accuracy of the reduced meteor spectral irradiance are: lack of measured atmospheric attenuation, the relatively unstable character of the film emulsion and developer, poor imagery, and the dense and nonuniform fog background of the spectral plates. The attenuation used here was taken from Elterman (1964).

The reduced absolute spectral irradiances are

TABLE 3.—*Wavelength Identifications of Geminid Meteor*

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3363	3361.92	11 Ca		1.89	5.56
	3362.13	11 Ca		1.89	5.56
3368	3369.57	6 Ni	2.1	0.00	3.66
3371	3370.79	304 Fe	32	2.68	6.34
	3371.99	7 Ni	0.41	0.16	2.84
3378	3379.02	85 Fe		2.17	5.82
3388	3388.17	23 Co	2.2	0.58	4.22
3400	3399.34	85 Fe	25	2.19	5.82
	3401.52	26 Fe		0.91	4.54
3407	3405.12	23 Co	15	0.43	4.05
	3407.46	83 Fe	33	2.17	5.79
3408	3409.18	23 Co	7.3	0.51	4.13
3412	3413.14	85 Fe	26	2.19	5.80
3416	3414.76	19 Ni	5.7	0.03	3.64
	3417.84	81 Fe	18	2.21	5.82
3420	3418.51	81 Fe	18	2.21	5.82
	3422.66	85 Fe	9.3	2.21	5.82
3425	3424.29	81 Fe	17	2.17	5.77
3441	3440.61	6 Fe	2.8	0.00	3.59
	3440.99	6 Fe	0.64	0.05	3.64
3449	3450.33	82 Fe	8.9	2.21	5.79
3459	3458.47	19 Ni	4.9	0.21	3.78

TABLE 3.—*Wavelength Identifications of Geminid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3462	3461.65	17 Ni	3.2	0.03	3.59
	3462.80	23 Co	9.7	0.63	4.19
3466	3465.86	6 Fe	0.52	0.11	3.67
3472	3472.54	20 Ni	1.2	0.11	3.66
3474	3474.02	4 Co	3.6	0.00	3.55
	3475.45	6 Fe	0.64	0.09	3.64
3485	3485.34	78 Fe	5.9	2.19	5.73
3490	3490.58	6 Fe	0.58	0.05	3.59
3495	3495.29	238 Fe	11	2.55	6.08
3497	3497.11	78 Fe	7.4	2.19	5.70
	3497.84	6 Fe	0.19	0.11	3.64
3499	3500.57	238 Fe		2.58	6.10
	3500.85	6 Ni		0.16	3.69
3514	3513.82	24 Fe	1.7	0.86	4.37
3521	3521.26	24 Fe	1.7	0.91	4.42
3524	3524.54	18 Ni	4.6	0.03	3.53
3527	3526.04	6 Fe	0.13	0.09	3.59
	3526.17	24 Fe	0.69	0.95	4.45
3531	3533.20	326 Fe	23	2.87	6.36
3536	3536.56	326 Fe	56	2.86	6.35
3542	3541.09	326 Fe	65	2.84	6.32
	3542.08	326 Fe	61	2.85	6.34
3566	3565.38	24 Fe	7.8	0.95	4.42
3570	3570.10	24 Fe	18	0.91	4.37
	3570.24	326 Fe		2.80	6.25
3581	3581.20	23 Fe	23	0.86	4.30
3596	3594.64	322 Fe	21	2.84	6.27
3606	3605.46	294 Fe	51	2.72	6.14
	3606.68	294 Fe	65	2.68	6.10
3608	3608.86	23 Fe	10	1.01	4.43
3618	3618.77	23 Fe	9.5	0.99	4.40
3621	3621.46	294 Fe	50	2.72	6.12
3631	3631.46	23 Fe	8.6	0.95	4.35
3640	3638.30	294 Fe	28	2.75	6.14
	3640.39	295 Fe	45	2.72	6.11
3644	3644.41	9 Ca	1.8	1.89	5.28
3649	3647.84	24 Fe	6.1	0.91	4.29
	3649.30	5 Fe		0.00	3.38
3660	3659.52	180 Fe	9.9	2.44	5.82
3671	3669.52	291 Fe	32	2.72	6.08
3680	3679.92	5 Fe	0.29	0.00	3.35
3685	3684.11	292 Fe	21	2.72	6.07
	3686.00	385 Fe	34	2.93	6.28
3687	3687.46	21 Fe	2.5	0.86	4.20
3696	3694.01	394 Fe	72	3.03	6.37
	3695.05	229 Fe	12	2.58	5.92
3698	3697.43	389 Fe		2.99	6.32
3707	3705.57	5 Fe	0.38	0.05	3.38
	3707.82	5 Fe	0.14	0.09	3.42
3720	3719.94	5 Fe	2.5	0.00	3.32
	3722.56	5 Fe	0.40	0.09	3.40
3738	3733.40	5 Fe	0.36	0.11	3.42
	3734.87	21 Fe	20	0.86	4.16

TABLE 3.—*Wavelength Identifications of Geminid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
	3737.13	5 Fe	1.5	0.05	3.35
3747	3745.56	5 Fe	1.2	0.09	3.38
	3745.90	5 Fe	0.31	0.12	3.42
	3748.26	5 Fe	0.71	0.11	3.40
	3749.49	20 Fe	13	0.91	4.20
3759	3758.24	21 Fe	10	0.95	4.24
3763	3763.79	21 Fe	6.2	0.99	4.26
3788	3787.88	21 Fe	1.7	1.01	4.26
3794	3795.00	22 Fe	2.3	0.99	4.24
3798	3798.51	21 Fe	0.93	0.91	4.16
	3799.55	21 Fe	1.5	0.95	4.20
3806	3805.34	608 Fe	45	3.29	6.53
	3806.70	607 Fe	21	3.25	6.50
3815	3815.84	45 Fe	16	1.48	4.71
3830	3827.82	45 Fe	15	1.55	4.77
	3829.35	3 Mg	11	2.70	5.92
3833	3832.51	3 Mg	23	2.70	5.92
3838	3838.26	3 Mg	39	2.70	5.92
3847	3846.80	664 Fe	20	3.24	6.45
3860	3859.91	4 Fe	1.4	0.00	3.20
3871	3872.50	20 Fe	1.0	0.99	4.17
3879	3878.02	20 Fe	1.4	0.95	4.14
	3878.58	4 Fe	0.33	0.09	3.27
3887	3886.28	4 Fe	0.63	0.05	3.23
	3887.05	20 Fe	4.2	0.91	4.09
3896	3895.66	4 Fe	0.14	0.11	3.28
3900	3899.71	4 Fe	0.21	0.09	3.25
3905	3905.53	3 Si	0.86	1.90	5.06
	3906.48	4 Fe	0.055	0.11	3.27
3924	3922.91	4 Fe	0.18	0.05	3.20
3935	3930.30	4 Fe	0.27	0.09	3.23
	3933.67	1 Ca II	0.91	0.00	3.14
3945	3944.03	1 Al	0.66	0.00	3.13
3948	3948.78	604 Fe	11	3.25	6.38
3962	3961.53	1 Al	1.3	0.00	3.13
3969	3968.47	1 Ca II	0.45	0.00	3.11
	3969.26	43 Fe	4.4	1.48	4.59
3983	3983.96	277 Fe	5.4	2.72	5.81
3999	3997.40	278 Fe	11	2.72	5.80
	3998.06	276 Fe	3.7	2.68	5.77
4005	4005.25	43 Fe	3.6	1.55	4.63
4008	4007.27	277 Fe		2.75	5.83
4011	4009.72	72 Fe	1.4	2.21	5.29
4032	4030.76	2 Mn	1.4	0.00	3.06
4035	4033.07	2 Mn	0.95	0.00	3.06
	4034.49	2 Mn	0.54	0.00	3.06
4046	4045.82	43 Fe	22	1.48	4.53
4063	4063.60	43 Fe	9.9	1.55	4.59
4069	4067.98	559 Fe		3.20	6.23
4072	4071.74	43 Fe	9.1	1.60	4.63
4101	4100.74	18 Fe		0.86	3.86
4109	4107.49	354 Fe	5.6	2.82	5.82
4115	4114.45	357 Fe		2.82	5.82

TABLE 3.—*Wavelength Identifications of Geminid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
4119	4118.55	801 Fe	33	3.56	6.55
4122	4121.32	28 Co	3.7	0.92	3.91
	4121.81	356 Fe		2.82	5.81
4133	4132.06	43 Fe	2.7	1.60	4.59
4136	4134.68	357 Fe	5.5	2.82	5.80
4144	4143.87	43 Fe	2.9	1.55	4.53
4151	4152.17	18 Fe		0.95	3.93
4153	4154.50	355 Fe	5.3	2.82	5.79
	4154.81	694 Fe		3.35	6.32
4171	4172.75	19 Fe		0.95	3.91
4176	4175.64	354 Fe	4.7	2.83	5.79
4181	4181.76	354 Fe	10	2.82	5.77
4184	4184.90	355 Fe	3.9	2.82	5.77
4190	4187.04	152 Fe	6.9	2.44	5.39
	4187.80	152 Fe	6.5	2.41	5.36
	4191.44	152 Fe	4.4	2.46	5.40
4200	4199.10	522 Fe	25	3.03	5.97
4202	4202.03	42 Fe	2.0	1.48	4.42
4209	4210.35	152 Fe	2.2	2.47	5.40
4218	4216.19	3 Fe	0.0031	0.00	2.93
	4219.36	800 Fe	27	3.56	6.48
4227	4226.73	2 Ca	1	0.00	2.92
	4227.43	693 Fe	38	3.32	6.24
4234	4233.61	152 Fe	5.9	2.47	5.39
4237	4235.94	152 Fe	7.9	2.41	5.33
4252	4250.79	42 Fe	1.5	1.55	4.45
	4250.13	152 Fe		2.46	5.36
4254	4254.35	1 Cr	2.0	0.00	2.90
4260	4260.48	152 Fe	15	2.39	5.29
4272	4271.76	42 Fe	5.2	1.48	4.37
4282	4282.41	71 Fe	2.0	2.17	5.05
4291	4289.72	1 Cr	0.95	0.00	2.88
	4291.66	3 Fe		0.09	2.99
4294	4294.13	41 Fe	0.71	1.48	4.35
4300	4299.24	152 Fe	5.2	2.41	5.29
4302	4302.53	5 Ca	7.1	1.89	4.76
4308	4307.91	42 Fe	5.9	1.55	4.42
4315	4315.09	71 Fe	1.5	2.19	5.05
4319	4318.65	5 Ca	2.5	1.89	4.75
4326	4325.76	42 Fe	6.1	1.60	4.45
4336	4337.05	41 Fe	0.23	1.55	4.40
4339	4339.45	22 Cr	0.93	0.98	3.82
	4339.72	22 Cr	0.30	0.96	3.80
4351	4351.77	22 Cr	2.0	1.03	3.86
4353	4352.74	71 Fe	1.0	2.21	5.05
4358	4358.51	412 Fe		2.94	5.77
4377	4375.93	2 Fe	0.0094	0.00	2.82
4384	4383.55	41 Fe	7.7	1.48	4.29
4404	4404.75	41 Fe	4.4	1.55	4.35
4415	4415.12	41 Fe	2.8	1.60	4.40
4426	4427.31	2 Fe	0.0099	0.05	2.84
4434	4434.96	4 Ca	3.5	1.88	4.66
	4435.69	4 Ca	0.96	1.88	4.66

TABLE 3.—*Wavelength Identifications of Geminid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
4442	4442.34	68 Fe		2.19	4.97
4455	4454.78	4 Ca	7.5	1.89	4.66
	4455.89	4 Ca	0.97	1.89	4.66
4462	4461.65	2 Fe	0.0052	0.09	2.85
4467	4466.55	350 Fe	5.3	2.82	5.58
4482	4482.17	2 Fe	0.0053	0.11	2.86
4531	4531.15	39 Fe	0.076	1.48	4.20
4580	4581.40	23 Ca	0.96	2.51	5.21
4585	4585.87	23 Ca	1.5	2.51	5.21
4646	4647.44	409 Fe		2.94	5.59
4878	4878.22	318 Fe	0.77	2.87	5.40
4890	4890.77	318 Fe	2.2	2.86	5.39
	4891.50	318 Fe	4.7	2.84	5.36
4920	4919.00	318 Fe	2.9	2.85	5.38
	4920.50	318 Fe	6.5	2.82	5.33
4960	4957.31	318 Fe	3.2	2.84	5.33
	4957.61	318 Fe	6.4	2.80	5.29
5007	5006.13	318 Fe	1.3	2.82	5.29
5108	5110.41	1 Fe	0.0014	0.00	2.41
5167	5166.29	1 Fe		0.00	2.41
	5167.34	2 Mg	1.2	2.70	5.09
	5167.49	37 Fe	0.26	1.48	3.87
	5168.90	1 Fe		0.05	2.44
5173	5171.60	36 Fe	0.12	1.48	3.86
	5172.70	2 Mg	3.5	2.70	5.09
5184	5183.62	2 Mg	6.4	2.70	5.09
5270	5269.54	15 Fe	0.098	0.86	3.20
	5270.36	37 Fe	0.20	1.60	3.94
5329	5328.05	15 Fe	0.087	0.91	3.23
5893	5889.95	1 Na	1.8	0.00	2.10
	5895.92	1 Na	0.9	0.00	2.09

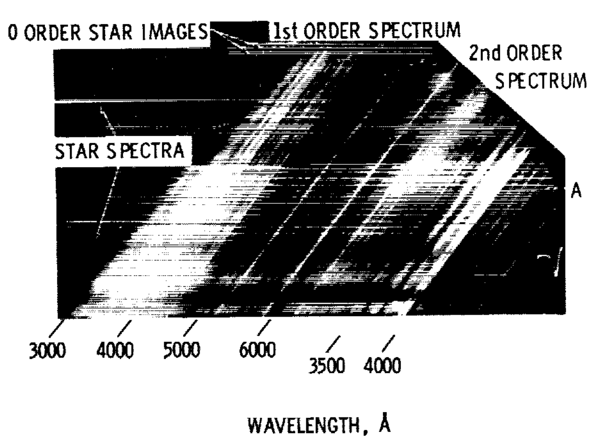

FIGURE 4.—Enlargement of a spectrogram of a Perseid meteor.

probably within a factor of 2 of the actual values, except perhaps for those in the near-ultraviolet region. In many cases, relative measurement of two lines in a spectrum (upon which most of the analysis is based) is estimated to be of the order of 5 to 10 percent accuracy. However, in some cases, especially where imagery is poor, the relative photometry suffers from blending of lines and the relative measurements are less accurate. The spectral irradiances of the four meteors are shown in figures 5 to 8.

DATA ANALYSIS

The data analysis is based on the assumption that the population distribution of the excited states is a Boltzmann distribution. Agreement in temperatures calculated from pairs of lines from

TABLE 4.—*Wavelength Identifications of Perseid Meteor*

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3090	3091.58	28 Fe	3.2	1.01	5.00
3102	3099.97	28 Fe	8.6	0.91	4.89
	3100.30	28 Fe	3.9	0.99	4.97
	3100.67	28 Fe	3.6	0.95	4.93
	3101.55	25 Ni	4.6	0.11	4.09
3135	3134.11	25 Ni	5.8	0.21	4.15
3192	3191.66	8 Fe	0.087	0.00	3.87
	3193.21	7 Fe	0.14	0.00	3.86
3240	3239.44	157 Fe	65	2.41	6.22
3265	3265.62	91 Fe	18	2.17	5.95
3298	3302.32	2 Na	0.65	0.00	3.74
	3302.99	2 Na	0.33	0.00	3.74
3348	3344.51	11 Ca		1.87	5.56
	3350.21	11 Ca		1.88	5.56
	3350.36	11 Ca		1.88	5.56
3370	3369.57	6 Ni	2.1	0.00	3.66
3385	3383.69	85 Fe		2.19	5.84
	3383.98	83 Fe	9.1	2.17	5.81
3422	3418.51	81 Fe	18	2.21	5.82
	3422.66	85 Fe	9.3	2.21	5.82
	3424.29	81 Fe	17	2.17	5.77
3441	3440.61	6 Fe	2.8	0.00	3.59
	3440.99	6 Fe	0.64	0.05	3.64
3472	3474.02	4 Co	3.6	0.11	3.66
	3475.45	6 Fe	0.64	0.09	3.64
3487	3485.34	78 Fe	5.9	2.19	5.73
3495	3495.29	238 Fe	11	2.55	6.08
3566	3565.38	24 Fe	7.8	0.95	4.42
	3570.10	24 Fe	18	0.91	4.37
3581	3581.20	23 Fe	23	0.86	4.30
3608	3608.86	23 Fe	10	1.01	4.43
3618	3618.77	23 Fe	9.5	0.99	4.40
3630	3631.46	23 Fe	8.6	0.95	4.35
3649	3647.84	24 Fe	6.1	0.91	4.29
3685	3684.11	292 Fe	21	2.72	6.07
	3686.00	385 Fe	34	2.93	6.28
3706	3705.57	5 Fe	0.38	0.05	3.38
	3707.82	5 Fe	0.41	0.09	3.41
3720	3719.94	5 Fe	2.5	0.00	3.32
	3722.56	5 Fe	0.40	0.09	3.40
3735	3733.40	5 Fe	0.36	0.11	3.42
	3734.87	21 Fe	20	0.86	4.16
	3737.13	5 Fe	1.5	0.05	3.35
3746	3745.56	5 Fe	1.2	0.09	3.38
	3745.90	5 Fe	0.31	0.12	3.42
	3748.26	5 Fe	0.71	0.11	3.40
	3749.49	20 Fe	13	0.91	4.20
3760	3758.24	21 Fe	10	0.95	4.24
3796	3795.00	22 Fe	2.3	0.99	4.24
3836	3827.82	45 Fe	15	1.55	4.77
	3829.35	3 Mg	11	2.70	5.92
	3832.51	3 Mg	23	2.70	5.92
	3838.26	3 Mg	39	2.70	5.92
3860	3859.91	4 Fe	1.4	0.00	3.20

TABLE 4.—*Wavelength Identifications of Perseid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
3887	3886.28	4 Fe	0.63	0.05	3.23
	3887.05	20 Fe	4.2	0.91	4.09
3902	3899.71	4 Fe	0.21	0.09	3.25
	3905.53	3 Si	0.86	1.90	5.06
3910	3909.84	364 Fe		2.83	5.99
3934	3933.67	1 Ca II	0.91	0.00	3.14
3968	3968.47	1 Ca II	0.45	0.00	3.11
4046	4045.82	43 Fe	22	1.48	4.53
4065	4063.60	43 Fe	9.9	1.55	4.59
4070	4071.74	43 Fe	9.1	1.60	4.63
4110	4107.49	354 Fe	5.6	2.82	5.82
4130	4132.06	43 Fe	2.7	1.60	4.59
4145	4143.87	43 Fe	2.9	1.55	4.53
4175	4175.64	354 Fe	4.7	2.83	5.79
4185	4184.90	355 Fe	3.9	2.82	5.77
	4187.80	152 Fe	6.5	2.41	5.36
4203	4202.03	42 Fe	2.0	1.48	4.42
4216	4216.19	3 Fe	0.0031	0.00	2.93
	4219.36	800 Fe	27	3.56	6.48
4227	4226.73	2 Ca	1.0	0.00	2.92
	4227.43	693 Fe	38	3.32	6.24
4255	4254.35	2 Cr	2.0	0.00	2.90
4273	4271.76	42 Fe	5.2	1.48	4.37
4292	4289.72	1 Cr	0.95	0.00	2.88
	4294.13	41 Fe	0.71	1.48	4.35
4307	4307.91	42 Fe	5.9	1.55	4.42
4325	4325.76	42 Fe	6.1	1.60	4.45
4378	4375.93	2 Fe	0.0094	0.00	2.82
	4384.55	41 Fe	7.7	1.48	4.29
4403	4404.75	41 Fe	4.4	1.55	4.35
4426	4427.31	2 Fe	0.0099	0.05	2.84
4460	4461.65	2 Fe	0.0052	0.09	2.85
4481	4481.13	4 Mg II		8.83	11.58
	4481.33	4 Mg II		8.83	11.38
	4482.17	2 Fe	0.0053	0.11	2.86
4571	4571.10	1 Mg		0.00	2.70
4585	4583.83	38 Fe II		2.79	5.49
4650	4649.14	1 O II		22.90	25.55
	4650.84	1 O II		22.87	25.52
4675	4673.75	1 O II		22.88	25.52
	4676.23	1 O II		22.90	25.53
4919	4919.00	318 Fe	2.9	2.85	5.36
	4920.50	318 Fe	6.5	2.82	5.33
4955	4957.31	318 Fe	2.2	2.84	5.33
	4957.61	318 Fe	6.4	2.80	5.29
5005	5006.13	318 Fe	1.3	2.82	5.29
5019	5018.78	13 O		10.69	13.15
	5019.34	13 O		10.69	13.15
	5020.13	13 O		10.69	13.15
5041	5041.06	5 Si II	0.473	10.02	12.47
5055	5056.02	5 Si II	0.380	10.03	12.47
	5056.35	5 Si II		10.03	12.47
5110	5110.41	1 Fe	0.0014	0.00	2.41

TABLE 4.—*Wavelength Identifications of Perseid Meteor*—Continued

λ measured (Å)	λ identified (Å)	Multiplet no.	gA ($\times 10^8$/s)	E_1 (eV)	E_2 (eV)
5142	5139.26	383 Fe	1.6	2.99	5.39
	5139.48	383 Fe	2.0	2.93	5.33
	5142.93	16 Fe		0.95	3.35
5170	5166.29	1 Fe		0.00	2.41
	5167.34	2 Mg	1.2	2.70	5.09
	5167.49	37 Fe	0.26	1.48	3.87
	5168.90	1 Fe		0.05	2.44
	5171.60	36 Fe	0.12	1.48	3.86
	5172.70	2 Mg	3.5	2.70	5.09
5184	5183.62	2 Mg	6.4	2.70	5.09
5226	5226.88	383 Fe	2.0	3.03	5.39
	5227.19	37 Fe	0.27	1.55	3.91
5269	5269.54	15 Fe	0.098	0.86	3.20
	5270.36	37 Fe	0.20	1.60	3.94
5328	5328.05	15 Fe	0.087	0.91	3.23
	5328.53	37 Fe	0.052	1.55	3.87
	5328.98	12 O		10.69	13.01
	5329.59	12 O		10.69	13.01
	5330.66	12 O		10.69	13.01
5343	5341.03	37 Fe	0.042	1.60	3.91
5370	5371.49	15 Fe	0.062	0.95	3.25
5428	5429.70	15 Fe	0.039	0.95	3.23
5453	5455.61	15 Fe	0.022	1.01	3.27
5525	5528.46	9 Mg	1.6	4.33	6.56
5570	5569.62	686 Fe	2.4	3.40	5.62
	5572.85	686 Fe	3.4	3.38	5.60
5586	5586.76	686 Fe	4.2	3.35	5.56
	5588.75	21 Ca	5.4	2.51	4.72
5775	5772.26	17 Si		5.06	7.20
5800	5797.91	9 Si		4.93	7.09
5893	5889.95	1 Na	1.8	0.00	2.10
	5895.92	1 Na	0.90	0.00	2.09
5960	5957.61	4 Si II	0.356	10.02	12.09
5980	5978.97	4 Si II	0.527	10.03	12.09
6000	5999.47	16 N		11.55	13.61
6123	6122.22	3 Ca	1.2	1.88	3.89
6155	6154.23	5 Na		2.09	4.70
	6155.99	10 O		10.69	12.70
	6156.78	10 O		10.69	12.70
	6158.20	10 O		10.69	12.70
6348	6347.09	2 Si II	0.31	8.09	10.03
6371	6371.36	2 Si II	0.387	8.09	10.02
6440	6439	18 Ca	3.2	2.51	4.43
6456	6453.64	9 O		10.69	12.61
	6454.48	9 O		10.69	12.61
	6456.01	9 O		10.69	12.61
6483	6481.73	21 N	0.0662	11.70	13.61
	6482.74	21 N		11.70	13.61
	6483.75	21 N		11.70	13.61
	6484.88	21 N	0.2725	11.70	13.61
6562	6562.82	1 H		10.15	12.04

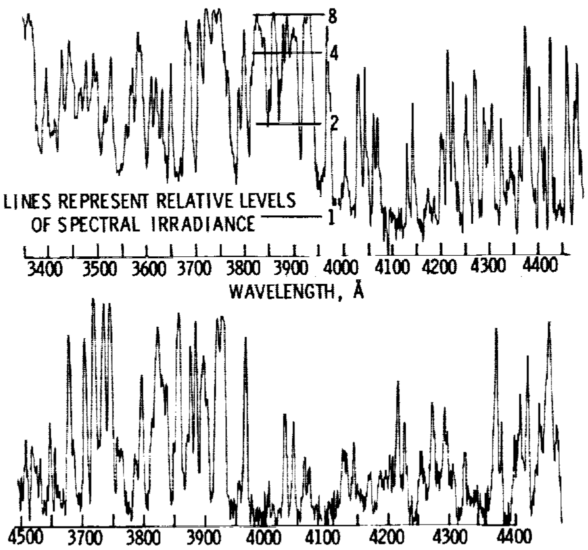

FIGURE 5.—Spectral irradiance from sporadic meteor.

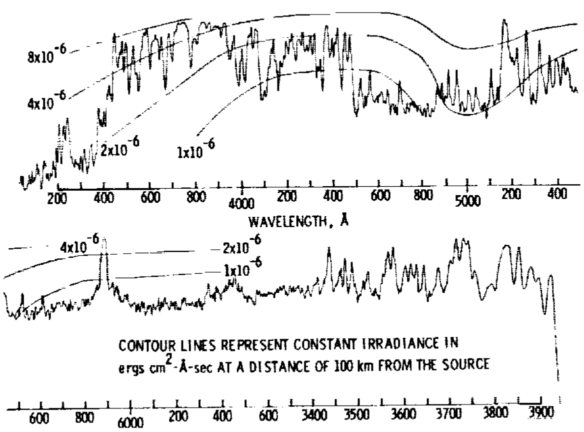

FIGURE 6.—Spectral irradiance from Taurid meteor.

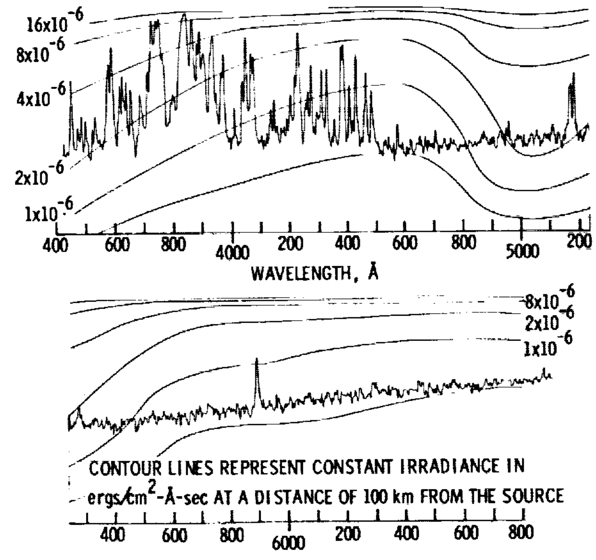

FIGURE 7.—Spectral irradiance from Geminid meteor.

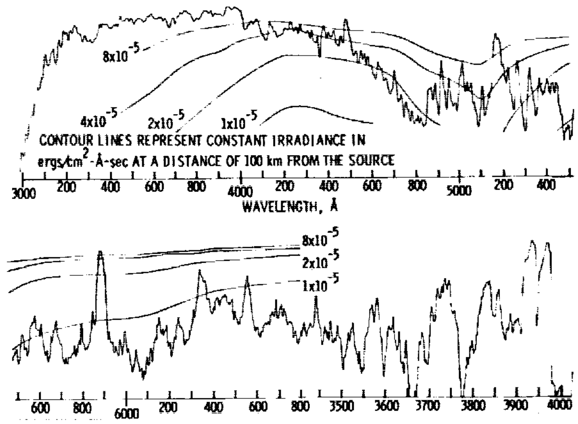

FIGURE 8.—Spectral irradiance from Perseid meteor.

several different energy levels is taken to be indicative that the excited state populations follow a Boltzmann distribution. In particular, the relative populations of the neutral excited states in the energy range of 2 to 6 eV are obtained. This is the energy region in which the number of lines in a good meteor spectrum allows one to measure the populations. Iron, because of the large number of lines of different energy levels, is a convenient reference element for these measurements.

As has been shown by Ceplecha (1964, 1967), Harvey (1970) and Millman (1932, 1935), the population distribution in this range is similar to that of a Boltzmann distribution. Especially for the fainter meteors, we can assume that all of the states are underpopulated relative to a gas in local thermodynamic equilibrium since the observed states are depopulated by radiative transfers (which occur quickly, compared to time between collisions). We can also assume that the very high (>6 eV) energy states are overpopulated relative to the lower energy states in local thermodynamic equilibrium (LTE) because of the high initial relative velocities of the ablated meteor atoms. However, as the underpopulation due to radiative transfer affects all the atoms and little radiation is observed from very high energy states (excluding ionic radiation), we can ignore these effects if we restrict ourselves to working on a relative basis and in a limited energy range.

The analysis, then, simply consists of selecting pairs of lines within the 2 to 6 eV energy range and computing an "effective meteor radiation temperature" T^*. Thus, T^* is calculated from

$$\frac{I_{in}}{I_{jl}}=\frac{h\nu_{in}N_iA_{in}}{h\nu_{jl}N_jA_{jl}}=\frac{h\nu_{in}g_iA_{in}}{h\nu_{jl}g_jA_{jl}}e^{-(E_i-E_j)/kT^*}$$

where I_{in} is the intensity of radiation for the transition from the ith to the nth atomic state, I_{jl} is the intensity of radiation for the transition from the jth to the lth atomic state, N_i is the number of particles in the ith atomic state with energy E_i above the ground state, h is Planck's constant, ν_{in} is the frequency of observed radiation for the transition from the ith to the nth state, g_i is the statistical weight of the ith state, A_{in} is the Einstein probability coefficient for the transition from the ith to the nth state, and k is the Boltzmann constant. The results of the calculations are shown in tables 5 to 8 for the sporadic, the Taurid, the Geminid, and the Perseid meteors, respectively. Excitation energies comparable to temperatures of hundreds of thousands of degrees are available in the initial meteor atomic collisions. General agreement in the range of T^* calculated from different pairs of lines indicates that the first atomic collisions do not dominate the meteor radiation process.

In general, table 5 reflects the advantage of high spectral resolution and its resultant effect

TABLE 5.—*Sporadic "Effective Meteor Radiation Temperature"*

Element	Lines (Å)	Temperature (° K)
Fe I	4384, 4376	2280
Fe I	3570, 3491	2453
Fe I	3648, 3680	2880
Fe I	4144, 4216	2540
Fe I	4404, 4427	2565
Fe I	av	2541±197 standard error

TABLE 6.—*Taurid "Effective Meteor Radiation Temperature"*

Element	Lines (Å)	Temperature (° K)
Fe I	4384, 4376	2490
Fe I	3570, 3441	3880
Fe I	3648, 3680	3360
Fe I	4405, 4427	2740
Fe I	4046, 4427	2570
Fe I	3631, 3707	3640
Fe I	3758, 3719	3870
Fe I	3581. 3719	3950
Fe I	4216, 4046	2260
	av	3196±640 standard error

TABLE 7.—*Geminid "Effective Meteor Radiation Temperature"*

Element	Lines (Å)	Temperature (° K)
Fe I	4384, 4376	2560
Fe I	3648, 3680	3680
Fe I	4405, 4427	2745
Fe I	4046, 4427	2800
Fe I	3631, 3707	4680
Fe I	3581, 3719	4150
Fe I	4046, 4216	2500
	av	3302±776 standard error

TABLE 8.—*Perseid "Effective Meteor Radiation Temperature"*

Element	Lines (Å)	Temperature (° K)
Fe I	4384, 4376	2780
Fe I	4405, 4427	2790
Fe I	4046, 4427	2670
Fe I	4046, 4216	2500
Fe I	5139, 5110	3970
	av	2942±525 standard error
Na I	5153, 5893	10,770
Ca I	6439, 4226	4470
Mg I	5528, 5184	12,810

on "effective radiation temperature" measurements. The Taurid measurements are compromised somewhat by overexposure. The Geminid measurements are relatively clean, while the Perseid measurements are poor because of bad imagery.

The abundances of elements relative to iron were computed by using the "effective radiation temperatures." That is, the atomic ratio of element a to element b, where element "b" is always iron, was obtained from

$$\frac{N_a}{N_b}=\frac{I_{ina}}{I_{jlb}}\frac{B(T)_a}{B(T)_b}\frac{g_{jb}A_{jlb}\nu_{jlb}}{g_{ia}A_{ina}\nu_{ina}}e^{-(E_{jb}-E_{ia})/kT^*} \quad (2)$$

where N_a is the number of atoms of element a, N_b is the number of atoms of iron, $B(T)_a$ is the partition function of element a, and $B(T)_b$ is the partition function of iron. Partition functions from Corliss (1962) were used. Iron was used as the reference element its prevalence in neutral spectra, and because of the large number of lines suitable for spectral measurements.

The ratios of the peak intensities of the relevant lines were used. The radiation of the element in question was compared to that of an iron line in the same spectral region, of similar energy level, and of comparable line strength where possible. The silicon determinations are highly uncertain because of the weakness of the 3905 Å line and the blending of other lines in this region of the spectrum. The element ratios calculated from the spectral measurements of the four meteors are presented in tables 9 to 12. "Derived compositions" based on the element ratios and typical meteorite oxygen abundances are also listed in the tables.

A dc arc was used as an empirical tool for data analysis. Some difficulty has been experienced in obtaining arc temperatures as low as some of the "equivalent radiation temperatures" of the meteors. Nevertheless, there is good general qualitative agreement between a dc arc and neutral meteor spectra. The arc studies indicate that the individual "equivalent radiation temperatures" obtained by this type of method are uncertain to several hundred degrees Kelvin for favorable line intensity measurements. The studies also show that reasonable silicon abundance measurements are possible with the 3905 Å line with high resolution and good plate quality.

TABLE 9.—*Element Ratios and "Derived Composition" of Sporadic Meteor*

Element ratios (atomic)	Derived composition (percent by weight)
$\frac{Ni}{Fe}=0.15$	Fe—68
$\frac{Ca}{Fe}=5.9\times10^{-5}$	Ni—10
$\frac{Mn}{Fe}=1.8\times10^{-3}$	Ca—0.0058
$\frac{Cr}{Fe}=2.2\times10^{-4}$	Mn—0.13
$\frac{Mg}{Fe}=1.16\times10^{-3}$	Cr—0.015
$\frac{Si}{Fe}=0.13$	Mg—0.19
	Si—9.8
	O—11

RADIATION

Four meteor spectra, each of more than 100 lines, have been reduced and analyzed. These four spectra of a sporadic, a Taurid, a Geminid, and a Perseid meteor may be taken as generally representative of bright meteor spectra in the optical range. The analyses of these spectra have shown a surprising simplicity and consistency of the radiation process for the neutral radiation.

The populations of the neutral excited states in the 2 to 6 eV energy range have been found to be consistent with that of a Boltzmann distribution within the experimental error. This may be taken as an indication that this type of radiation is produced by a gas that is near equilibrium. A physical concept that can be correlated with these measured results is as follows: meteoric gas is initially energized by the passage and ablation of a meteoroid. The following "relaxation and mixing" of this energized gas probably involves hundreds of collisions within milliseconds. The relaxation and mixing can be considered in terms of the downward velocity cascade of meteoric atoms (and impacted atmospheric molecules) through a series of collisions with atmospheric molecules. For a simple elastic hard sphere

TABLE 10.—*Element Ratios and "Derived Composition" of Taurid Meteor*

Element ratios (atomic)	Derived composition (percent by weight)
$\frac{Ni}{Fe}=0.106$	Fe—13
$\frac{Ca}{Fe}=1.5\times10^{-4}$	Ni—1.6
$\frac{Mn}{Fe}=3.2\times10^{-4}$	Ca—0.0015
$\frac{Cr}{Fe}=5.1\times10^{-4}$	Mn—0.0043
$\frac{Mg}{Fe}=1.8$	Cr—0.0068
$\frac{Si}{Fe}=4.6$	Mg—10
$\frac{Na}{Fe}=8.1\times10^{-5}$	Si—30
$\frac{Al}{Fe}=1.7\times10^{-2}$	Na—0.00045
	Al—0.11
	O—44

TABLE 11.—*Element Ratios and "Derived Composition" of Geminid Meteor*

Element ratios (atomic)	Derived composition (percent by weight)
$\frac{Ni}{Fe}=0.114$	Fe—13
$\frac{Ca}{Fe}=2.0\times10^{-3}$	Ni—1.7
$\frac{Mn}{Fe}=4.0\times10^{-4}$	Ca—0.02
$\frac{Cr}{Fe}=5.1\times10^{-4}$	Mn—0.0055
$\frac{Mg}{Fe}=2.06$	Cr—0.0068
$\frac{Si}{Fe}=4.2$	Mg—12
$\frac{Na}{Fe}=1.0\times10^{-4}$	Si—27
$\frac{Al}{Fe}=1.9\times10^{-2}$	Na—0.00057
	Al—0.13
	O—45

model, the most probable energy transfer from an incident atom to a target atom has been calculated to be of the order of 25 percent of the incident atom energy. For a simple series of collisions with atmospheric molecules at rest, more than 20 collisions are required for a typical meteoric atom of 30 km/s initial velocity to "cool" to a velocity of 1.26 km/s (which corresponds to a 4000° K gas velocity). This simple cascade is a minimum case, as both a more realistic atomic scattering potential and collision-increased atmospheric-molecule velocity will decrease the most probable energy transfer to less than 25 percent of the incident atom energy. However, even the minimum number of collisions is sufficient for the velocity distribution to approach that of an equilibrium gas. In some cases, a Boltzmann distribution has been shown to be closely approached after only three collisions per particle (Kittel, 1958).

Some complication is introduced because the radiation that is photographed with a streak camera or spectrograph is a composite of the radiation from the series of collisions. That is, this radiation results initially from a few very high energy collisions, from many more collisions of moderate energy at a longer and later instant when the gas is approaching equilibrium, of many, many more collisions of moderately low energy at a still later time when the gas is very close to an equilibrium velocity distribution, and, finally, of still more collisions when the gas is practically in equilibrium, but still cooling and radiating as the meteor wake. This interpretation is in general agreement with radiation times and energy levels observed in wake and flare radiation (Harvey, 1971b).

It appears, from the time-integrated spectral measurements, that superposition of radiation from all of the radiation times results in a spectrum that is similar to that of a gas near equilibrium. This probably results from the initial collisions being too few and having too broad a spectrum (many energy levels can be excited) to dominate the radiation, and the later wake radiation being too energy-limited to dominate

TABLE 12.—*Element Ratios and "Derived Composition" of Perseid Meteor*

Element ratios (atomic)	Derived composition (percent by weight)
$\frac{Ca}{Fe}=3.9\times10^{-4}$	Fe—13
$\frac{Mn}{Fe}=4.9\times10^{-4}$	Ca—0.0037
$\frac{Cr}{Fe}=1.1\times10^{-3}$	Mn—0.0064
$\frac{Mg}{Fe}=0.68$	Cr—0.014
$\frac{Si}{Fe}=5.6$	Mg—3.9
$\frac{Na}{Fe}=5.2\times10^{-5}$	Si—36
	Na—0.00028
	O—45
	H—?

the spectrum. Thus, an intermediate case must dominate. The relatively few initial high energy collisions will tend to average the many inefficient low energy collisions to an intermediate case.

However, this does not mean that all meteor radiation is simple or straightforward. Resonance or nonequilibrium effects are observed in all detailed studies of radiation sources, be they flames, arcs, stellar atmospheres, or other sources. This obviously is the case with the strong ionic emissions in bright, fast meteors. This is evidenced by the absence of such radiation in faint meteors, and the absence of normally expected ionic lines. Several articles concerning *H* and *K* radiation are in the literature (Harvey, 1971b; Hoffman, 1971; Hoffman and Longmire, 1968; Rajchl, 1963). The observed Mg II and Si II radiation is even more anomalous because of its higher energy levels and the absence of many normally strong ion lines.

As significant as the general agreement in "effective radiation temperatures," shown in tables 5 to 8, is the fact that there is no identified neutral iron radiation that is not in general agreement with a Boltzmann distribution. The same is true of other neutral spectra where there are enough suitable lines to make a meaningful measurement. Thus, all of the neutral line radiation appears well behaved, the expected lines are present and are at the expected intensity, unexpected lines are not present.

We may conclude, then, that optical meteor radiation does not result from just the initial collisions of meteoric atoms with atmospheric molecules, but by a complete energy-cascade-via-collisions process. Since this involves at least tens to hundreds of collisions, it is basically a statistical process, and can be treated in terms of equilibrium distributions (over limited ranges) and deviations from equilibrium. The radiation can also be treated in terms of individual atomic cross sections but this requires even more detailed knowledge of the meteor conditions.

COMPOSITION

The measurement of composition need not be strongly dependent upon the assumption that the excited state populations are given by a Boltzmann distribution. The composition measurements require only that the meteor radiation processes of the relevant spectral lines be basically the same. That is, the population distribution of excited states of different atoms need to be similar. The distribution does not even need to be known very well, if the energy levels of the excited states chosen for measurement are close together.

If the meteoric excitation process is selective with respect to one atom over another, then problems may arise. However, since optical meteor excitation is basically collisional, that is, no radiative coupling occurs, it is unlikely that neutral radiation excitation is significantly selective in light of the consistency of the "effective radiation temperature measurements." Selectivity does, of course, show up in the ionic radiation and renders these lines unstable for abundance measurements. This need not prevent the use of neutral radiation for composition measurements.

Perhaps the most notable result of the measurement of the four meteors is that they are indicative of nickel-iron or stony meteorite composition. However, it should be noted that the sodium and calcium abundances are very low compared to cosmic or meteorite abundances. No effects such as neutral atom depletion by ionization, incomplete dissociation, or self absorption in the meteor plasma have been considered in these preliminary abundance values. Such effects will be considered in a subsequent paper.

The significant elements which have not been obtained from the analysis are oxygen, carbon, and hydrogen (silicon has already been discussed). Reasonable values for the abundances of oxygen can be obtained from those elements with which it is combined in meteorites. Carbon is not expected in major abundances, but is important for studies of meteorite origin and evolution. The best hope for measured carbon abundances is probably the very difficult one of measuring carbon band systems. Needless to say, observational difficulties for these measurements are extreme. A somewhat unexpected result is the strength of Hα in bright, fast meteor spectra. Little hydrogen would generally be expected after repeated passes of a meteoroid at distances of less than 1 AU from the Sun. Both the high energy level of the excited state and the low atomic weight (and hence low kinetic energy) are significant aspects of the hydrogen radiation which will require serious consideration.

CONCLUDING REMARKS

Four spectra, which are believed to be generally representative of the spectra of brighter meteors obtained by the Faint Meteor Spectra Patrol, have been reduced and analyzed. The neutral line radiation from these meteors was determined to be similar to that of a gas in equilibrium at a relatively low temperature. These results demonstrate that the powerful concept of local thermodynamic equilibrium can be fruitfully applied to meteor spectroscopy. In the past, poor quality of spectral data and the dominance of anomalous ionic radiation in much of the better spectra have served as deterrents to detailed quantitative analysis of meteor spectra. Thus, it is hoped that the present results will hasten the transition of meteor spectroscopy from primarily qualitative studies which have characterized it in the past to detailed quantitative studies which improved data now warrant.

The "derived composition" of the slow sporadic meteor appears to be generally similar to that of a typical nickel-iron meteorite. The "derived compositions" of the three shower meteors appear to be similar to and seem to indicate stony meteorite composition. These "derived compositions," although presently the most comprehensive direct data on meteor composition, are early results that are expected to be rapidly supplemented by additional data of even greater quality and quantity.

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