# 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.

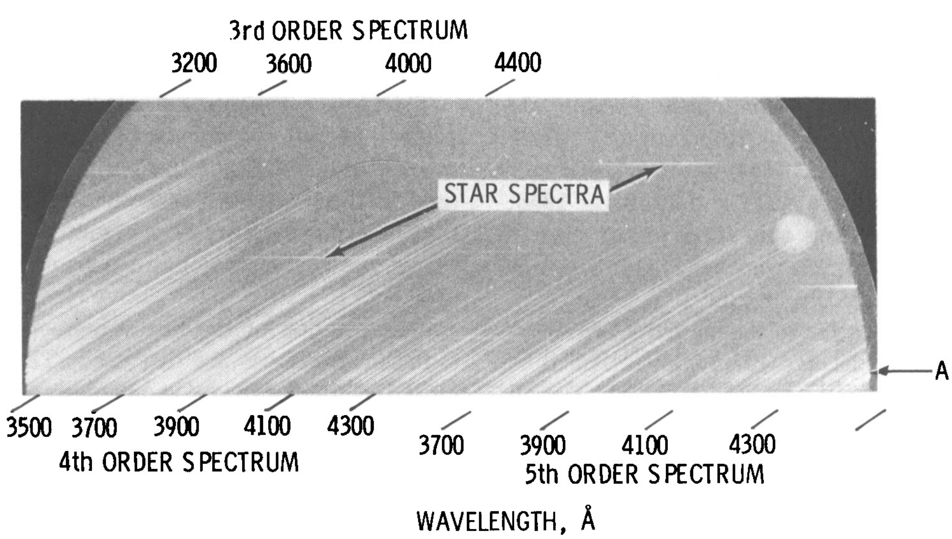


FIGURE 1.—Enlargement of spectrogram of a sporadic meteor.

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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 |

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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

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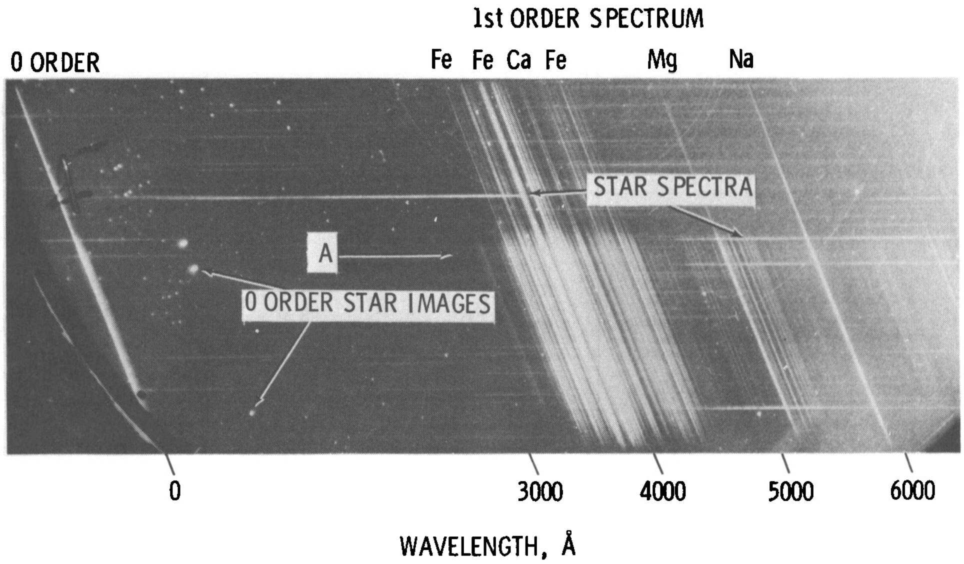


FIGURE 2.—Enlargement of a spectrogram of a Taurid meteor.

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 |

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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 |

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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

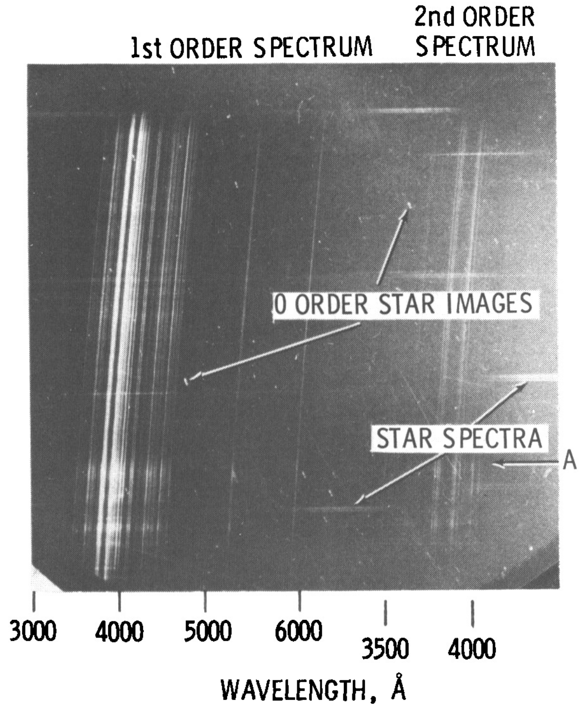


FIGURE 3.—Enlargement of a spectrogram of a Geminid meteor.

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 |

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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 |

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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 |

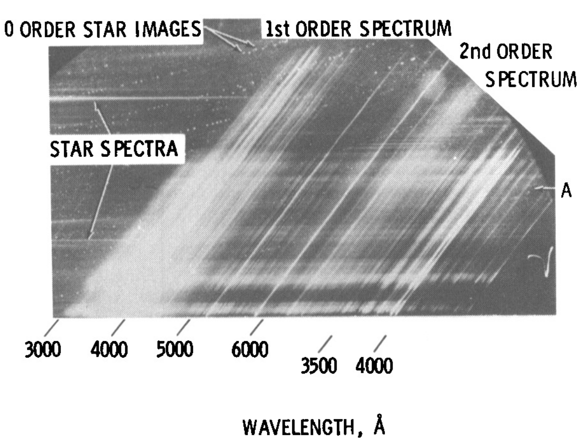


FIGURE 4.—Enlargement of a spectrogram of a Perseid meteor.

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 |

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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 |

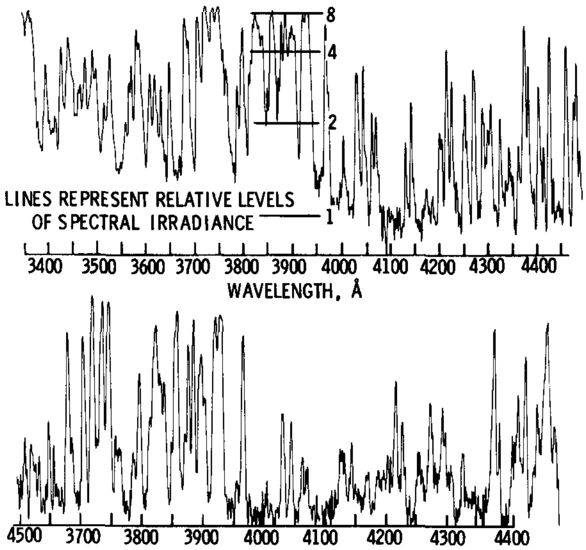


FIGURE 5.—Spectral irradiance from sporadic meteor.

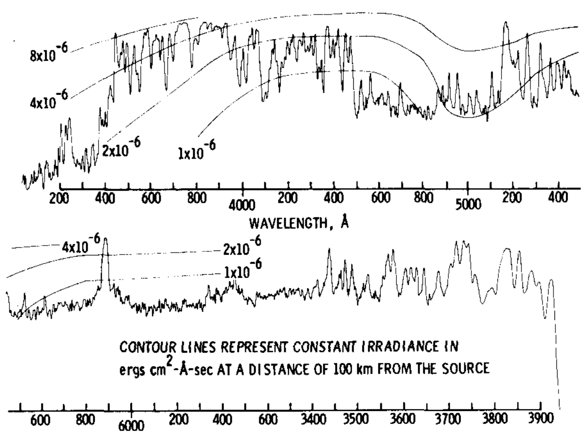


FIGURE 6.—Spectral irradiance from Taurid meteor.

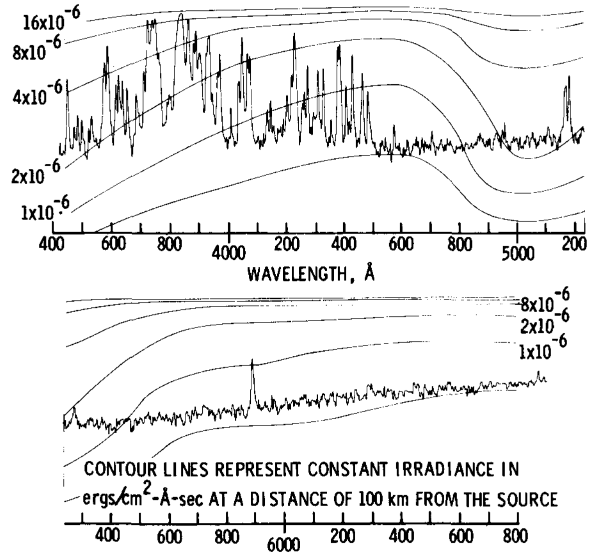


FIGURE 7.—Spectral irradiance from Geminid meteor.

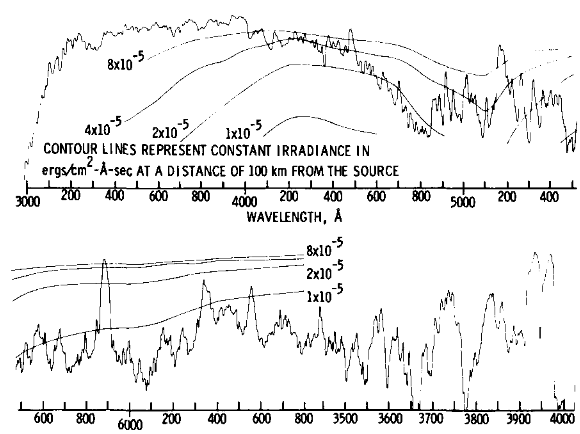


FIGURE 8.—Spectral irradiance from Perseid meteor.

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

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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 $i$th to the $n$th atomic state, $I_{jl}$ is the intensity of radiation for the transition from the $j$th to the $l$th atomic state, $N_i$ is the number of particles in the $i$th atomic state with energy $E_i$ above the ground state, $h$ is Planck's constant, $\nu_{in}$ is the frequency of observed radiation for the transition from the $i$th to the $n$th state, $g_i$ is the statistical weight of the $i$th state, $A_{in}$ is the Einstein probability coefficient for the transition from the $i$th to the $n$th 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 | 2544±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 H$\alpha$ 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.

## REFERENCES


Ayers, W. G., McCrosky, R. E., and Shao, C. -Y., 1970. Photographic observations of 10 artificial meteors, *Smithson. Astrophys. Obs. Spec. Rept.* No. 317, 1–40.

Ceplecha, Z., 1964. Study of a bright meteor flare by means of emission curve of growth, *Bull. Astron. Inst. Czech.*, **15**, 102–112.

——, 1965. Complete data on bright meteor 32281, *Bull. Astron. Inst. Czech.*, **16**, 88–101.

——, 1967. Spectroscopic analysis of iron meteoroid radiation, *Bull. Astron. Inst. Czech.*, **18**, 303–310.

Cook, A. F., Jacchia, L. G., and McCrosky, R. E., 1963. Luminous efficiency of iron and stone asteroidal meteors, *Smithson. Contrib. Astrophys.*, **7**, 209–220.

Corliss, C. H., 1962. Ionization in the plasma of a copper arc, *J. Res. Nat. Bur. Standards*, **66A**, 169–175.

Corliss, C. H., and Bozman, W. R., 1962. *Experimental transition probabilities for spectral lines of seventy elements*, NBS Monograph **53**, U.S. Dept. of Commerce, Washington.

D'Aiutolo, C. T., Kinard, W. H., and Nauman, R. J., 1967. Recent NASA meteoroid penetration results from satellites, *Smithson. Contrib. Astrophys.*, **11**, 239–251.

Elterman, L., 1964. Atmospheric attenuation model, 1964, in the ultraviolet, visible, and infrared regions for altitudes to 50 km, *U.S. Air Force Environ. Res. Papers* No. 46 (AFCRL–64–740), Sept. 1964, 1–40.

Griem, H. R., 1964. *Plasma Spectroscopy*, McGraw-Hill Book Co., New York, 580 pp.

GRYGAR, J., KOHOUTEK, L., AND PLAVCOVÁ, Z., 1968. Simultaneous radar and optical observation of meteors at Ondřejov in 1962, in *Physics and Dynamics of Meteors*, edited by Ľ. Kresák and P. M. Millman, D. Reidel Publ. Co., Dordrecht, Holland, 63–69.

HALLIDAY, I., 1961. A study of spectral line identifications in Perseid meteor spectra, *Publ. Dominion Obs.*, **25,** 1–16.

——, 1969. A study of ultraviolet meteor spectra, *Publ. Dominion Obs.*, **25,** 315–322.

HARVEY, G. A., 1967a. Photometry of spectrograms of three artificial meteors, *NASA Tech. Note* **D-3930,** 1–30.

——, 1967b. A method of slitless absolute spectral photometry, *NASA Tech. Note* **D-3765,** 1–20.

——, 1970. Spectra of faint optical meteors, unpublished.

——, 1971a. The NASA LRC faint meteor spectra patrol, *NASA Tech. Note* **D-6298,** 1–25.

——, 1971b. The calcium *H*- and *K*-line anomaly in meteor spectra, *Astrophys. J.*, **165,** 669–671.

HOFFMAN, H. S., 1971. Ionic spectra of meteors, *Astrophys. J.*, **163,** 393–403.

HOFFMAN, H. S., AND LONGMIRE, M. S., 1968. Meteor ion spectra, *Nature*, **218,** 858–859.

JACCHIA, L. G., VERNIANI, F., AND BRIGGS, E., 1967. An analysis of the atmospheric trajectories of 413 precisely reduced photographic meteors, *Smithson. Contrib. Astrophys.*, **10,** 1–139.

KITTEL, C., 1958. *Elementary Statistical Physics*, J. Wiley and Sons, New York, 228 pp.

LINDBLAD, B. A., 1963. The relation between visual magnitudes and the durations of radar echoes, *Smithson. Contrib. Astrophys.*, **7,** 27–39.

MILLMAN, P. M., 1932. An analysis of meteor spectra, *Harvard College Obs. Ann.*, **82,** 113–146.

——, 1935. An analysis of meteor spectra: second paper, *Harvard College Obs. Ann.*, **82,** 149–177.

——, 1967. Some characteristics of the major meteor showers, *Smithson. Contrib. Astrophys.*, **11,** 105–108.

MOORE, C. E., 1945. A multiplet table of astrophysical interest, *Contrib. Princeton Univ. Obs*, No. 20.

RAJCHL, J., 1963. A short note on meteor spectra with low dispersion, *Smithson. Contrib. Astrophys.*, **7,** 155–156.