13. An Unusual Meteor Spectrum

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An extraordinary spectrum of a meteor at a velocity of about 18.5±1.0 km s^{-1} *(approximate uncertainty) was observed from the Springhill Meteor Observatory with an image-orthicon camera at 1970 August 10* ^{d} 2^{h} 48^{m} 51^{s} *UT. The radiant of the meteor was at an altitude of about 49°. It was first seen showing a yellow-red continuous spectrum alone at a height of 137±8 km (estimated uncertainty) which we ascribe to the first positive group of nitrogen bands. At 1.60*^{s} *after its initial appearance the meteor had descended to 116±6 km above sea-level when it brightened rapidly from its previous threshold brighness into a uniform continuum. After a further 0.73*^{s} *at a height of 106±6 km the D-line of neutral sodium appeared and 0.14*^{s} *later (height 105±5 km) all the other lines of the spectrum also appeared. The continuum remained dominant to the end 0.40*^{s} *later (height 87±5 km) or 3.87*^{s} *after initial appearance.*

Water of hydration and entrained carbon flakes of characteristic dimension about 0.2 micron or less are proposed as constituents of the meteoroid to explain these phenomena.

THE METEOR DISCUSSED in this paper was observed on the cooperative program of meteor observation commenced in 1969 at the Springhill Meteor Observatory. This program involves the use of an image-orthicon tube, backed up by auxiliary information from meteor radars and spectrographs, and a visual observing team (Millman et al., 1971).

TRAJECTORY

The meteor was observed by the G.E. image-orthicon camera model 4TE17A1 containing a specially selected GL 7967 image-orthicon tube with an S–20 photocathode and fitted with a 50 mm camera lens at $f/0.95$ and a Bausch and Lomb replica transmission grating (300 lines mm^{-1}, blazed at 17°27′) described by Hemenway et al. (1971). The observation was made from the Springhill Meteor Observatory at Springhill, Ontario (latitude 45°12′ N, longitude $5^h1.9^m$ W, elevation 102 m). The meteor radars and spectrographs, and the visual team were not operating at the time of the meteor's appearance. The meteor appeared at 1970 August $10^d2^h48^m51^s$ UT. The output of the image-orthicon tube was recorded on an Ampex 7000 video tape recorder along with time signals from CHU. The video tape was played back through a television monitor which was photographed on 16 mm motion picture film with a Bolex H–16 camera at a rate of 15 frames s^{-1} with individual exposures of about 1/30 s. The film was projected on the back side of a ground glass screen for tracing, measurement and analysis. Further details of this equipment are given by Hemenway et al. (1971). A star field was also observed with the grating removed at $2^h0^m0^s$ UT.

The star field was traced and used to establish a grid of right ascension and declination for the equinox of 1855 by use of the *Atlas des nördlichen gestirnten Himmels* (Schönfeld and Krüger, 1899). The positions of the meteor spectrum together with the zero order, when available, and the sodium *D*-line in all available orders (out to the third in some frames) were also plotted. Also the zero orders of α and β Cassiopeiae were marked.

The nominal coordinates read off were right ascension and declination for the equinox of 1855 fitted to the star field at $2^h0^m0^s$ UT. These were precessed forward for 116 years to the equinox of 1971. They were next transformed to local hour angle and declination at Springhill and then to azimuth and altitude at Springhill. As expected the "observed" values for the zero orders of α and β Cassiopeiae did not match their computed directions at $2^h48^m51^s$ UT. The dispersion of the grating was parallel to the horizon at the centre of the field so that we expected a shift in azimuth only unless the camera had been moved when the grating was attached. This evidently did happen so that our final azimuths and altitudes were reached by transforming from our zenith without the grating to a new zenith at azimuth 45° E of N, altitude 89.0° and shifting these azimuths by a correction of −3.9°.

A final shift to a system of coordinates along the trail with pole at the pole of the trail was made, longitude along the trail being reckoned from the point of the trail's highest declination on the 1855 coordinate system. On this system the curvature of the 1st and 2nd orders was evident; the latitudes covered the ranges 6.9° to 6.0° and 14.2° to 14.0° respectively. The 3rd order was seen on only a few frames at latitude 22.5°. Reductions in longitude in the sense zero order minus order were found as follows: 1st order +4.6°, 2nd +10.4°, 3rd +16.2°. The adopted longitudes of the zeroth order were the mean from all observed

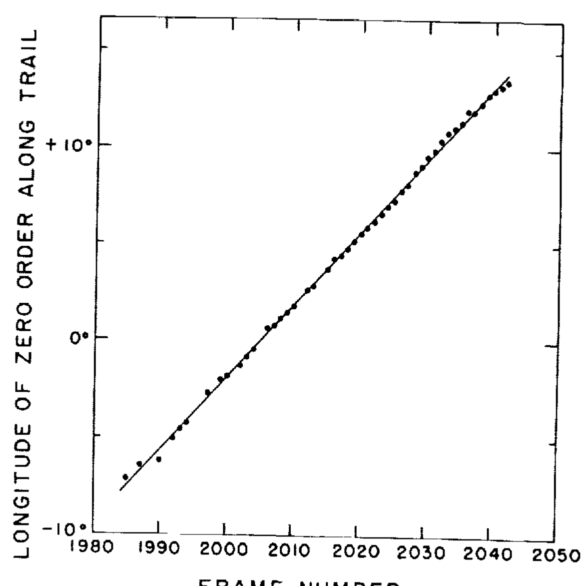

FIGURE 1.—Longitude of zero order image of meteor along trail as a function of kinescoped frame number.

orders for each frame. Figure 1 exhibits the resulting plot of longitude along the trail versus frame number (linear with time) and the adopted fit which appears to be a straight line.

If we read off from the fit of figure 1 three longitudes at equal intervals of frame number (and thus also of time) we may construct the plane triangles exhibited in figure 2. Let L denote longitude along the trail, the subscript 2 the middle epoch and the subscripts 1 and 3 the initial and final epochs respectively. Then the angular distances from the initial epoch to the middle epoch and from the middle epoch to the final epoch are α_1, α_2 respectively and the distances travelled along the trajectory are

$$D_1 \equiv D_2 \equiv D \equiv V(t_2-t_1) \equiv V(t_3-t_2) \qquad (1)$$

where V is the velocity of the meteor, t_1 is the initial epoch, t_2 is the middle epoch and t_3 the final epoch. The corresponding ranges are R_1, R_2 and R_3. By the law of sines we have

$$\frac{\sin\alpha_1}{D}=\frac{\sin\theta_1}{R_1}=\frac{\sin(\pi-\alpha_1-\theta_1)}{R_2}=\frac{\sin(\alpha_1+\theta_1)}{R_2}$$

$$\frac{\sin\alpha_2}{D}=\frac{\sin\theta_2}{R_3}=\frac{\sin(\pi-\alpha_2-\theta_2)}{R_2}=\frac{\sin(\alpha_2+\theta_2)}{R_2} \qquad (2)$$

where the angles θ_1, θ_2 are indicated in figure 2. Evidently we have

$$\theta_1+\theta_2\equiv\pi \qquad (3)$$

and θ_2 is the angular distance from the radiant at the middle epoch. Elimination of θ_1 from equations (2) and (3) yields

$$\frac{\sin\alpha_2}{\sin\alpha_1}=\frac{\sin(\theta_2+\alpha_2)}{\sin(\theta_2-\alpha_1)} \qquad (4)$$

a transcendental equation to be solved for θ_2. In the present case we have from figure 1, $L_1=-7.5°$, $L_2=+3.15°$, $L_3=+13.8°$ and $\alpha_1=\alpha_2=10.65°$ both estimated as uncertain by $\pm0.10°$. The result is plainly $\theta_1=\theta_2=90.0°$ and the uncertainty can be shown by differentiation of equation (4) to be $\Delta\theta_2=\pm2.8°$. This is the internal uncertainty of the position of the radiant along the trail. The internal uncertainty normal to the trail is $\pm0.6°$. We estimate the corresponding external uncertainty due to paucity of stars here and there in the field of view at about $\pm10°$ and $\pm2°$ respectively.

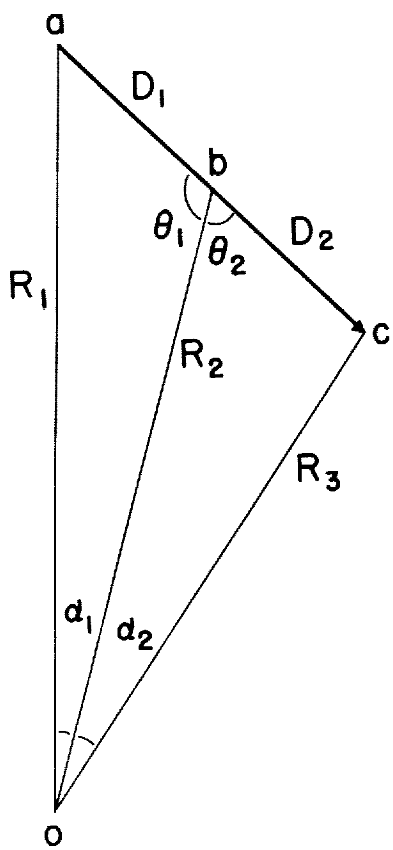

FIGURE 2.—Plane triangles formed by the meteor's trajectory and the observing station. The meteor was at a, b, and c at epochs 1, 2, and 3 respectively and at ranges R_1, R_2, and R_3, respectively. The observed angular lengths of the corresponding segments of the trail are α_1 and α_2.

The adopted longitude of the radiant along the trail is $-86.8°$. This transforms to azimuth 172.5°, altitude 48.6°, local hour angle $-4.8°$, declination $+4.0°$, right ascension 289.7° (1971) and finally to celestial longitude 292.0°, latitude $+26.2°$. The meteoric apex was calculated by a formula from Olivier (1925) to be at celestial longitude 47.8°. The elongation from the meteoric apex was 103.1°.

We then turned to figure 5, p. 12 of Jacchia and Whipple (1961) which exhibits the geocentric velocity, V_G, as a function of elongation of the geocentric radiant from the meteoric apex for 413 meteors. At 103° from the apex there is a principal maximum of population over the range $15 < V_G < 19$ km s^{-1} which corresponds to $19 < V_\infty < 23$ km s^{-1} where V_∞ denotes the velocity outside the atmosphere. A secondary concentration occurs just under the parabolic limit at $V_G = 24$ km s^{-1}. Occasional stragglers appear at lower velocities. The length of the trail is so long even for the part which shows the spectrum of vapours of meteoritic material that evidently we were looking at a meteor of Ceplecha's (1968) Class C. We sought that velocity which best fits the expected end height from his figure 27, p. 42. The procedure commenced with a succession of trial values of $V_\infty \simeq V$ which then allowed us to compute corresponding values of D and of the ranges, which from equations (2) and (3) are

$$R_1 = D\frac{\sin\theta_2}{\sin\alpha_1}, \quad R_2 = D\frac{\sin(\theta_2+\alpha_2)}{\sin\alpha_2}, \quad R_3 = D\frac{\sin\theta_2}{\sin\alpha_2} \qquad (5)$$

then heights above sea-level were read off from a graph of isolines of constant height with range as abscissa and altitude as ordinate (used in routine reductions of meteors observed at Springhill). An extract from these calculations appears in table 1. We adopted 18 km s^{-1} as the best fit.

The best overall compromise appears to lie at the mean of the lower edge of the principal maximum of Jacchia and Whipple's (1961) distribution and the best fit to the end height for Ceplecha's (1968) Class C. Thus we finally adopted a velocity of 18.5±1.0 km s^{-1} (estimated uncertainty).

TABLE 1.—*End Heights Computed for Various Velocities Compared with Those Expected for Ceplecha's (1968) Class C*

Velocity, V (km s^{-1})	Corresponding end height, H_e (km)	End height, H_e for Ceplecha's Class C (km)	Difference (km)
16	74	82	−8
17	79	82	−3
18	84	83	+1
19	90	83	+7

At this point diurnal aberration was removed followed by zenith attraction both for the radiant and the velocity. The geocentric radiant and velocity were then transformed to the heliocentric radiant and velocity and an orbit determined. The assembled results appear in table 2.

THE SPECTRUM

The most convenient way to describe the spectrum is in the form of a chronology, table 3.

TABLE 2.—*Circumstances of the Meteor*[a,b]

Frame no.	Epoch (s)	Description	1971 R.A. (deg)	1971 Decl. (deg)	Azimuth E from N (deg)	Altitude (deg)	Range (km)	Height (km)
1985	0.00	Beginning	2.7	+67.8	31.9	45.6	190±10	137±8
2013.5	1.90	Middle epoch	30.1	+68.5	26.1	36.2	187±10	112±6
2042	3.80	Final epoch	55.1	+64.5	21.7	26.3	190±10	87±5
2043	3.87	End						87±5
		App. radiant			172.5	48.6		
		Geoc. radiant	288.5	−0.7				

[a] The meteor appeared at 1970 August 10^d 2^h 48^m 51^s UT.

[b] Velocity outside the atmosphere is approximately equal to velocity in the atmosphere, i.e., 18.5±1.0 km s^{-1}; geocentric velicity is 14.7 km s^{-1}. Geocentric radiant from celestial longitude is 289.8°, latitude +21.4° (1971). Elongation from meteoric apex is 106.8°. Orbital elements: $a = 2.5$ AU, $e = 0.66$, $\omega = 236°$, $i = 9°$, $\Omega = 137°$, $P = 3.9$ y, $q = 0.84$ AU, $Q = 4.1$ AU, $\pi = 13°$.

Details of the spectrographic identifications are listed in table 4.

PROPOSED EXPLANATION

We attempt a very tentative explanation of the foregoing sequence of events. We note that the radiations of molecular nitrogen remained approximately constant during a descent through 21 km in height. This implies that the surface area being struck by air molecules decreased with height in such a way as to nearly cancel the rise in atmospheric density. This may be explained if most of the exposed surface belonged to fragments shed from the meteoroid. In that case the fragments must have been so small as to have been stopped locally and must have been shed at a rate decreasing so as to cancel the rise in density of the atmosphere.

A frontal surface element must have radiated in an environment somewhere between the two extremes of radiation from a flat surface into a hemisphere with perfect insulation in the other hemisphere and isotopic radiation into the entire sphere. At an accommodation coefficient of unity for a very rough surface (Öpik 1958, pp. 52–54) and for radiation with emissivity unity (Öpik 1958, p. 55) into a hemisphere oriented in the direction of flight, the temperature of the surface in radiative equilibrium with the heat flux from the air stream at the beginning of the meteor was $500° \pm 70°$ K (U.S. Committee, etc. 1962). For isotropic radiation over a sphere it was $350° \pm 50°$ K. We may adopt as a rough estimate $430° \pm 100°$ K. Such a temperature suggests release of water of hydration. It is common for such a release to break down the affected substance into a powder. In this way we account for the initial appearance of the meteor.

Fresh surface would have been exposed by this process and while it would have continued it is entirely reasonable to expect that more and more of the exposed area would have been resistant to

TABLE 3.—*Chronology of Events*

Epoch (s)	Height (km)	Event
0.00	137±8	At this initial appearance only a yellow-red continuum can be seen which we ascribe to the 1st positive group of N_2 by analogy with other spectra (Millman et al. 1971). Next the 2nd positive group appeared in the blue-violet and near UV. Both features remained near threshold until the next epoch.
1.60	116±6	A general brightening occurred into a uniform continuum.
1.90	112±6	This is the middle frame of the measured path.
2.33	106±6	The *D*-line of Na appeared.
2.47	105±5	Other lines of the spectrum appeared.
3.80	87±5	This is the last measured frame.
3.87	87±5	Here the meteor ended abruptly, the *D*-line having brightened very roughly in proportion to atmospheric density all the way with the continuum remaining dominant right to the end. Maximum absolute photographic magnitude of the meteor was very approximately zero. Identifications of spectral features are listed in table 4. Frames of the spectrum near the end are exhibited in figure 3.

TABLE 4.—*Spectral Features*[a]

Wave-length Å	Order	Intensity	Element and multiplet or molecule and group
3500	2	Weak	Fe (6)
3600	2	Weak	Fe (23)
3725	2	Medium	Fe (5), (21)
3835	2	Strong	Mg (3)
3890	2	Medium	Fe (4), (20)
4050	2	Weak	Fe (43)
4227	2	Medium	Ca (2)
4571	2	Weak	Mg (1)
4900	2	Medium	Fe (318)
5177	1, 2	Strong	Mg (2)
5300–5400	1, 2	Medium	Fe (15)
5520	1, 2	Medium	
5892	1, 2 3	Very Strong	Na (1)
6130	1	Weak	[b] N_2, 1^+
6450–6650	1	Weak	[b] N_2, 1^+

[a] The numbers of the multiplets are those assigned by Moore (1945).

[b] The entry N_2, 1^+ refers to molecular nitrogen, first positive group.

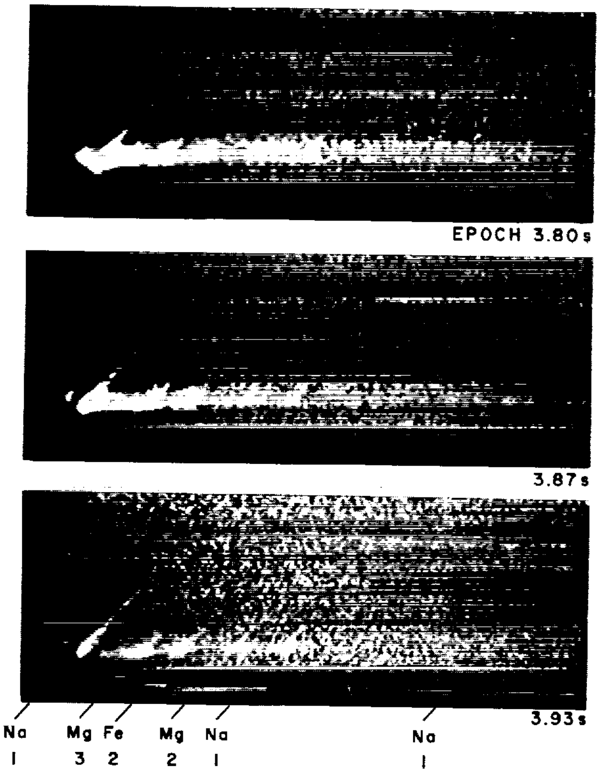

FIGURE 3.—Three kinescoped frames of the spectrum near the epoch of disappearance of the meteor.

complete collapse as the water of hydration was baked away. In that way we account for the failure of the meteor to brighten until 1.60^{s} after the appearance and through a descent of 21 km.

The sudden brightening at 1.60^{s} occurred when the two limiting temperatures in radiative equilibrium had reached $1400° \pm 130°$ K and $1000° \pm 90°$ K. We may estimate $1200° \pm 150°$ K. At this temperature we postulate the onset of melting of baked out portions of the surface and their spinning off in droplets by rotation of the meteoroid to explain the brightening. This melting would have had the character of surface tension overcoming viscosity (Cook, 1968, p. 153), perhaps pulling together adjacent elements. Sizes up to the limit set by the critical Bond number (Cook, 1968, p. 154) would have been possible for the stone droplets. An explanation of the continuum is required. Here we tentatively suggest entrained carbon flakes which were not hydrated and were small compared with the wavelengths radiated, i.e., of characteristic radii of a few tenths of a micron. Their small emissivities would have sent their temperatures up possibly to that appropriate to loss of heat largely by vaporization. The high temperature of vaporization of a refractory substance like carbon combines with the expected decrease of emissivity with increasing wavelength for very small particles to produce a relatively bluish continuous radiation.

The appearance of vaporized sodium at 2.33^{s} signaled the rise of the spun off droplets of stone to the temperature required to release sodium. Then general vaporization corresponding to the usual beginning of a meteor began at epoch 2.47^{s}. All the foregoing implies ablation as small fragments of stone, later as fragments of some refractory substance such as carbon and droplets of stone, and finally as vaporizing fragments of carbon and droplets of stone.

It is an evident consequence of these ideas that after the onset of melting and spraying new surfaces still loaded with water of hydration would have been exposed so that crumbling would have occurred followed by melting and spraying. Random phasing of these successive processes across the surface of the meteoroid would have rapidly developed.

While all the foregoing is plausible if not subject to proof, the final feature—the steady rise to an abrupt end without a flare—is more difficult. Only an extremely tentative triad of assumptions has occurred to us. Since the area subject to vaporization was apparently roughly constant during this interval we assume that (1) the cloud of stone droplets and refractory (carbon) flakes was steadily replenished at the required rate. The abrupt ending requires then that (2) the final breakup of the meteoroid was into droplets similar in size to those still travelling in the cloud and further that (3) their size was small enough to allow abrupt exhaustion of the droplets and thus of the meteor.

CONCLUDING REMARKS

This paper reports an entirely new behavior of meteoric spectra. Only an instrument as sensitive as the television system used, or one still more sensitive, can detect these very faint phenomena, and more observations are urgently required to pass beyond the speculations presented above to a more satisfactory understanding of the faint early portions of meteor spectra dominated by bands and continua.

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