14. Spectroscopy of Project Fire I, April 14, 1964

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The Fire I test, April 14, 1964, was designed to study the heating of an Apollo-type reentry vehicle. The total reentry complex weighed approximately 230 kg and entered the upper atmosphere at a velocity of 11.5 km/s. The spectrum of the reentry complex has been studied in the wavelength range 3700 to 8800 Å, where 102 multiplets of 21 atoms and the band systems of 5 diatomic molecules have been identified. Comparisons with meteor spectra are made.

THE WRITER OF THIS PAPER served as a part-time consultant at the Avco Everett Research Laboratory during the period 1962 to 1967 (Millman, 1968). The work at Avco involved the study of the spectra of various reentry objects resulting from the tests made in the space-research program of the United States. One of the tests that has recently been declassified is Project Fire I, the high-speed reentry of a scaled-down model of the Apollo Command Module. This was launched from Kennedy Space Center, Florida, at $21^h 42^m 25^s$ UT, April 14, 1964. The reentry was sighted at $22^h 10^m 02.5^s$ UT over a point at lat. 08.8° S, long. 14.9° W, height 92 km, just southwest of Ascension Island. Photographic coverage by Avco was carried out from three aircraft flying to the northeast of the reentry track at heights between 2.5 and 4.3 km. This experiment produced what were, in effect, a number of very brilliant artificial fireballs, and it is of interest to study the spectrum of the luminosity in relation to comparable studies of bright meteors.

OBSERVATIONAL DATA

The complete reentry event of Project Fire I involved the reentries of the main rocket body, the Apollo model (termed the reentry package, R/P), an Antares II–A5 rocket motor with housing (termed the velocity package, V/P), and several other unidentified pieces of hardware. The R/P was in the form of a blunt-faced vehicle 64.5 cm in diameter with a conical after-body 53.6 cm long, and weighed 86.6 kg. The V/P was cylindrical in form, approximately 356 cm long and 76 cm in diameter, with a spent weight of 143.8 kg. Most of the data given here concerning the R/P, the V/P, and their reentry trajectory are taken from Popper et al. (1965). For more detailed information concerning the mechanical construction, including the chemical elements involved, see McKee (1966). Over most of the trajectory covered by the spectrographs, that is, above 50 km, the R/P and V/P were too close together to be separated on the record and the spectrum photographed is a composite of the two bodies. For convenience these will be referred to as the Fire Reentry Complex, FR/C.

The R/P was designed to study the heating of a blunt, high-speed reentry vehicle and the radiation emitted by it. It was equipped with six heat shields on its forward surface and these were ejected at various heights, measured by both telemetry and photography. Details concerning the heat shields are listed in table 1. The weight of the R/P was 40 percent heat shields, 40 percent electronics and 20 percent structure.

TABLE 1.—*Heat Shields on Fire I Reentry Package*

No., counting from the outside	Material	Thickness (cm)	Approximate ejection height (km)
1	Beryllium calorimeter	0.25	70—66
2	Phenolic heat shield	0.50	58—56
3	Beryllium calorimeter	0.50	50—46
4	Phenolic heat shield	0.50	43—40
5	Beryllium calorimeter	0.25	36—32
6	Phenolic heat shield	1.00	

TABLE 2.—*Observed Velocity of Fire I Reentry Complex*

Height (km)	Velocity (km/s)
90	11.5
75	11.5
65	11.3
55	10.6
50	9.9
45	8.8
40	7.0

The observed velocity of the FR/C is given in table 2. The trajectory was inclined at 13.3° to the horizontal and the visible portion extended for over 220 km in length from a height of 92 km down to 41 km above sea level. Several isolated bursts were observed still lower. The projection of the trajectory on the ocean surface had an angle of 122° from true north through east, taken in the direction of motion.

Photometry of the visible radiation in the range 4000 to 6500 Å gave results consistent among three independent recordings taken from two aircraft. For comparison with meteor observations these data, expressed in watts per steradian (Popper et al., 1965), have been reduced to absolute panchromatic magnitude, M_{pan}, by multiplying by 4π and assuming a total radiation of 0.126 W as equivalent to $M_{pan}=0$. A summary of the photometry is listed in table 3. The first part of the table refers to the complete FR/C. The four brightest bursts, well off scale for the photometric record, were due to the breakup of the V/P. From 56 km down, the magnitudes refer to the R/P only. Comparison with table 1 will show maxima in luminosity at the heights where the heat shields were rejected.

Spectrograms of the FR/C for Project Fire I were obtained with four K-24 cameras, mounted on a DC-6 aircraft flying at 3.65 km altitude. The lenses were of 17.8 cm focal length, aperture ratio $f/2.5$, and were fitted with objective transmission gratings, 300 lines/mm, giving a dispersion of 187 Å/mm in the first order at the center of the field. Three spectrographs were run with Eastman Royal-X Pan film, the fourth with Eastman Aero IR film, and a K2 filter. Exposures of 2 s each were made continuously and the data acquisition period was 28 s for one of the spectrographs loaded with panchromatic film and about 20 s for the other three spectrographs. The distance from the aircraft to the FR/C varied between 175 and 120 km during the period of data acquisition.

SPECTROGRAPHIC IDENTIFICATIONS

The general identification of the atomic and molecular features appearing in the Fire I spectra were made by a group, which included the writer, at the Avco Everett Laboratory under the direction of Charles C. Petty and Richard M. Carbone. Many of these identifications have been illustrated in Popper et al. (1965). However, the present writer is responsible for the selection of the data and the height analysis given here. In general, measurement of the spectra was carried out using enlarged photographic prints (about 16×) and the original films were only used for identification of fine detail, or for examination of the very faint features.

The typical appearance of Fire I spectra is illustrated in figures 1 and 2, where many of the more prominent molecular bands and atomic-line multiplets are marked for identification. In the case of the atomic lines the multiplet numbers used are from Moore (1945), while for the molecules the vibrational band sequences only have been indicated, with Pearse and Gaydon (1963) as the primary reference. Heights in kilometers are placed at the left of the corresponding levels in the spectra, which are oriented in the figures with motion downward. The last spectra shown, under 50 km height, are primarily of the R/P only while the remainder are for the FR/C.

TABLE 3.—*Photometry of Fire I Reentry Complex, April 14, 1964*

UT 22h 10m +	Height (km)	M_{pan}	Remarks
02.5 s	91.6	−13.1	Photometric threshold
02.8	91.2	−14.2	Luminosity Max.
03.3	89.9	−13.1	Min.
03.8	88.6	−14.6	Max.
04.1	87.6	−13.6	Min.
04.5	86.6	−14.8	Max.
05.0	84.9	−13.2	Min.
05.8	83.2	−14.4	Max.
06.1	82.1	−14.0	Min.
06.5	81.2	−14.5	Max.
07.1	79.5	−13.6	Min.
07.9	77.5	−14.6	Max.
08.2	76.7	−14.2	Min.
08.7	75.3	−15.1	Max.
09.1	74.2	−14.6	Min.
09.9	72.4	−16.7	Shelf in light curve
10.5	70.5	−18.8	Max.
11.2	68.7	−16.4	Min.
11.8	67.3	−20.5	Luminosity increasing rapidly and record goes off scale
13.0	64	<−21	Brilliant burst
13.5	63	<−21	Very brilliant burst
15.2	59	<−21	Very brilliant burst
15.8	57	<−21	Most brilliant burst
16.2	56.4	−17.7	Record begins again
16.5	55.5	−18.3	Rapid oscillations
16.8	54.9	−19.4	Max.
17.4 18.9	53.5 50.0	−13.5 to −17.0	Rapid oscillations
19.4	48.8	−17.9	Max.
20.0 20.5	47.5 46.5	−16.5 to −17.5	Rapid oscillations
20.5	46.2	−19.9	Max.
20.8 22.0	45.5 42.5	−14.5 to −15.5	Rapid oscillations
22.2	42.1	−19.1	Max.
22.5	41.4	−15.8	Luminosity decreasing and oscillating
23.1	40.1	−13.2	Final spectrographic record
	35.6	−17.1	Max.
	32.6	−19.1	Max.

Vibration of the cameras in the aircraft is evident in many of the spectra as wavy lines. These are more marked for some cameras and for the features where the luminosity is of short duration. Evidence for a wake of Na and AlO luminosity, and possibly CaCl, is seen at the beginning of the overexposed frame at 64½ km in figure 2.

HEIGHTS OF SPECTROGRAPHIC FEATURES

Heights for the various spectrographic exposures are available from the trajectory analysis, carried out by Avco using direct photographs. The first feature visible on the spectrograms is

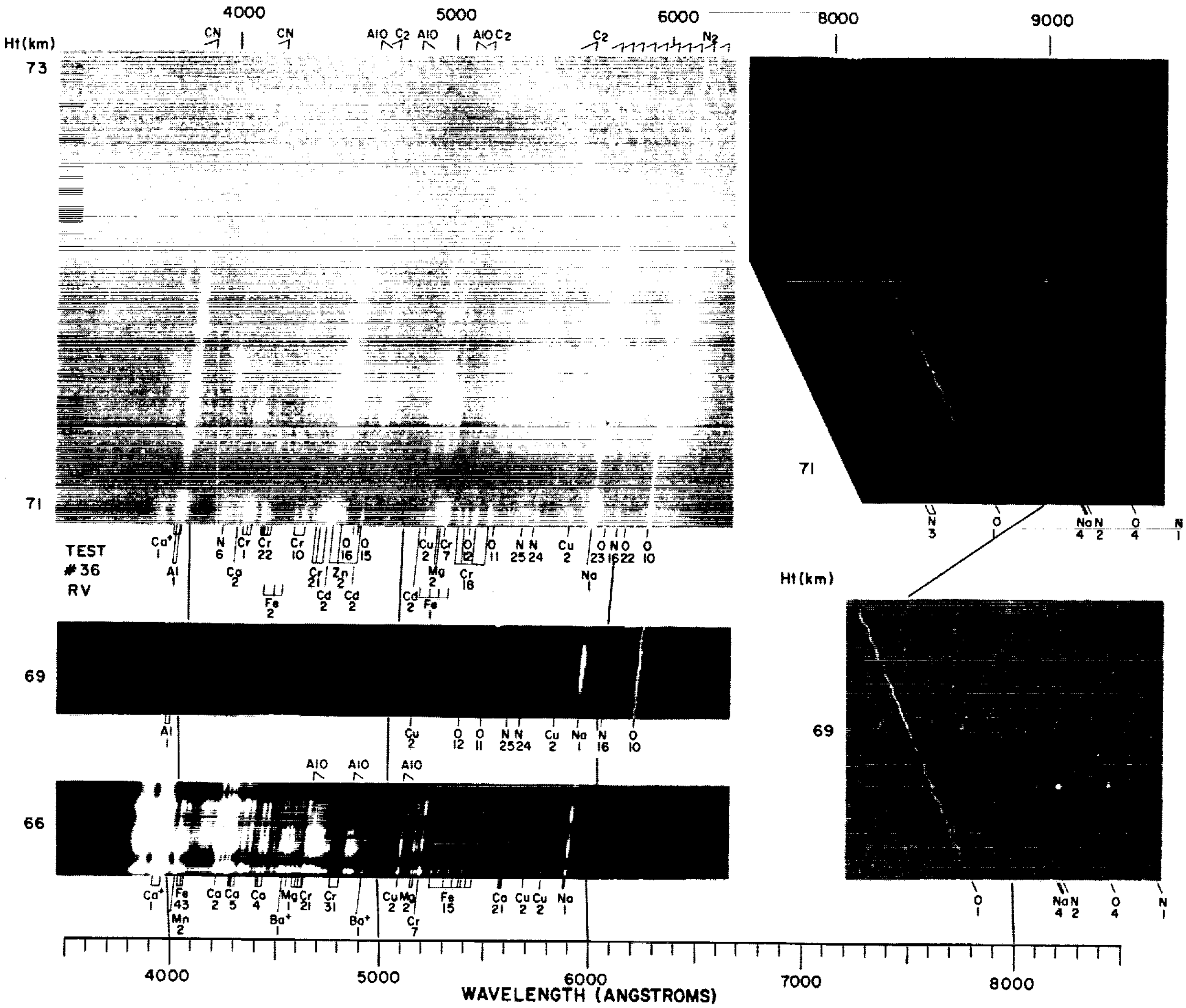

FIGURE 1.—Examples of spectra of the Fire I Reentry Complex from the upper part of the trajectory. Multiplet numbers are from Moore, 1945. The spectrum at 66 km is reproduced from the second order as the first order was overexposed.

the cyanogen band system in the violet, which appears at a height of 88.5 km. This is quickly followed by the first positive band system of nitrogen in the red at 87.5 km and the violet lines of neutral aluminum at 84.5 km. A listing of the heights of first appearance for all features identified is given in table 4. This table includes 102 multiplets of 18 neutral atoms and 3 singly ionized atoms, and the band systems of 5 diatomic molecules. These atoms and molecules are:

H, Li, Be, N, O, Na, Mg, Al, K, Ca, Ca^+, Ti, Cr, Mn, Fe, Cu, Zn, Sr^+, Cd, Ba, Ba^+,

BeO, C_2, CN, N_2, AlO.

This is not claimed to be a complete list but it does include most of the easily seen features.

The height of disappearance is difficult to determine in many cases owing to the rapidly varying luminosity and to the overexposure in the bursts. Most of the atomic lines fade out between 55 and 50 km, after the breakup of the V/P. Some multiplets of Mg, Ca, Cr, Cu, Zn,

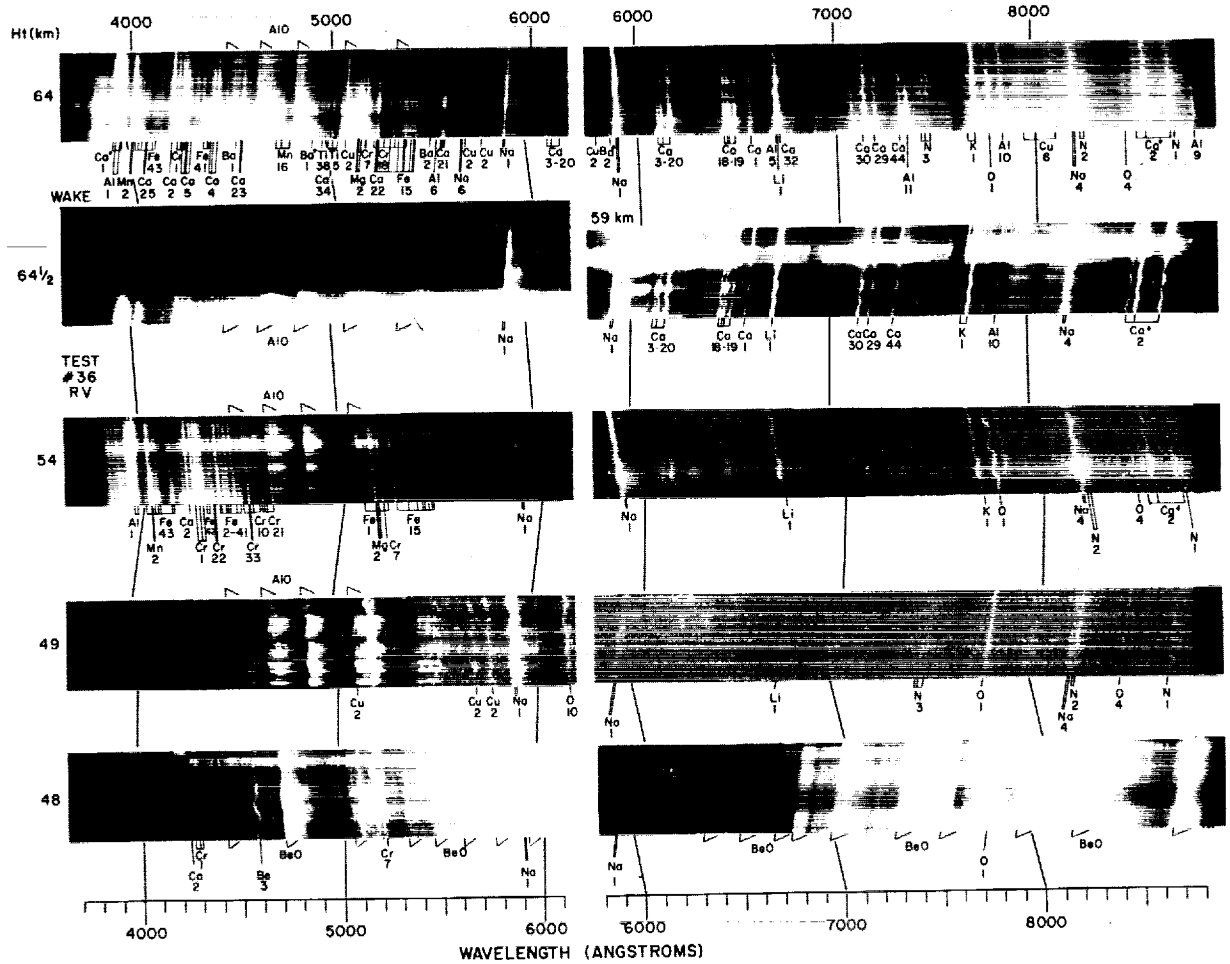

FIGURE 2.—Examples of spectra of the Fire I Reentry Complex from the lower part of the trajectory. Multiplet numbers are from Moore, 1945. The panchromatic spectra at 64 and 54 km are reproduced from the second order as the first order was overexposed.

and Cd are visible a little below 50 km, while Na and K remain down to the end of the spectrographic record near 40 km height. Bands of CN and N_2 disappear near 70 km, but C_2 is recorded down to 65 km and AlO to just below 50 km. It is possible that, in addition to the molecules listed, bands of CaCl and CaF are present in the 65 to 55 km range. The rejection of the beryllium heat shields produces a strong Be and BeO spectrum starting just below 50 km. Some 20 or more BeO band sequences have been identified (Pearse and Gaydon, 1963; Herzberg, 1933; Lagerquist, 1948) in the blue-green and the red systems. These remain visible down to the end of the spectrographic record.

DISCUSSION

The general range of heights observed in the Fire I spectrum is similar to the range for spectra of slow fireballs (Millman, 1971) extended to somewhat greater heights of appearance. The early appearance of the CN and N_2 bands is of interest in relation to the faint band structure observed with image-orthicon equipment at the beginning of meteor trajectories (Millman et al.,

TABLE 4.—*Heights of the Initial Appearance of Features in the Fire I Reentry-Complex Spectrum*

Height (km)	Multiplet numbers (Moore, 1945) and molecular band sequences[a]
88.5	CN (3883, 4216)$_{b}$
87.5	N_2 (first positive)$_{c}$
84.5	Al I (1)$_{b}$
79.0	O I (1)$_{b}$
78.0	O I (10)$_{b}$
77.0	N I (2)$_{e}$
74.0	O I (4)$_{e}$
73.5	N I (1)$_{d}$ (16)$_{d}$, O I (40?)$_{g}$
73.0	N I (24)$_{e}$ (25)$_{e}$, O I (12)$_{e}$, Na I (1)$_{a}$ (4)$_{b}$, C_2 (4737, 5165, 5636)$_{c}$
72.0	N I (3)$_{e}$ (6)$_{e}$ (10)$_{f}$, O I (11)$_{g}$ (22)$_{f}$ (23)$_{g}$, Ca I (2)$_{b}$, Ca II (1)$_{b}$, Cr I (1)$_{b}$ (7)$_{b}$ (21)$_{d}$, Cu I (2)$_{c}$, AlO (4648, 4842, 5079)$_{b}$
71.5	O I (15)$_{e}$ (16)$_{f}$ (17)$_{e}$ (18)$_{f}$, Mg I (2)$_{c}$, Cr I (10)$_{e}$ (18)$_{b}$ (22)$_{c}$, Mn I (2)$_{b}$, Fe I (1)$_{f}$ (2)$_{f}$ (3)$_{g}$, Cd I (2)$_{e}$
71.0	Zn I (2)$_{e}$
68.0	Mg I (1)$_{d}$, Ca I (3)$_{c}$ (4)$_{e}$ (5)$_{e}$ (18)$_{c}$ (19)$_{c}$ (20)$_{c}$ (21)$_{c}$ (22)$_{c}$ (23)$_{e}$ (25)$_{f}$, Cr I (6)$_{g}$ (8)$_{f}$ (31)$_{f}$ (60)$_{f}$ (145)$_{f}$ (185?)$_{g}$, Fe I (15)$_{c}$ (41)$_{f}$ (42)$_{f}$ (43)$_{f}$, Sr II (1)$_{g}$, Ba I (2)$_{e}$, Ba II (1)$_{d}$ (2)$_{e}$
65.0	H I (1)$_{f}$, Li I (1)$_{b}$, N I (8)$_{g}$, Na I (5)$_{d}$ (6)$_{e}$ Al I (5)$_{e}$ (6)$_{f}$ (9)$_{d}$ (10)$_{d}$ (11)$_{d}$, K I (1)$_{c}$, Ca I (1)$_{d}$ (29)$_{d}$ (30)$_{d}$ (31)$_{g}$ (32)$_{e}$ (34)$_{g}$ (41)$_{g}$ (44)$_{d}$ (47)$_{d}$ (48)$_{g}$ (49)$_{g}$, Ca II (2)$_{c}$, Ti I (4?)$_{g}$ (5)$_{c}$ (6)$_{c}$ (38)$_{d}$ (42)$_{e}$ (44)$_{e}$ (106)$_{c}$, Mn I (16)$_{d}$, Cu I (6)$_{g}$, AlO (4470, 5337)$_{e}$
55.0	Mg I (3)$_{d}$, Fe I (4)$_{e}$ (16)$_{g}$ (20)$_{f}$ (37)$_{g}$ (68)$_{f}$
48.0	Be I (3)$_{e}$, BeO (>20 band sequences, 4180–8712)$_{a}$, AlO (4307)$_{g}$

[a] The subscripts a, b, c, d, e, f, g, in this table form a qualitative scale which indicates the degree of prominence of each feature in a descending sequence of values.

1971; Papers 12 and 13, this volume). As in the case of the faster cometary meteors (Millman, 1971) the atomic lines of O and N appear in Fire I relatively high compared to the rest of the spectrum. They remain visible to heights below 50 km, which is lower than normally observed in meteors. In contrast to most meteor spectra, where the input of atoms from the meteoroid has a fairly constant composition along the trail, reentry spectra exhibit a nonhomogeneous structure resulting from a diversity of atomic input into the radiating vapor. A good example is the spot appearances of Cu, Cr and Fe at different heights between 73 and 71 km, figure 1. It has also been found that trace elements in a reentry vehicle may appear in the spectrum with unexpected prominence. This warns us against a superficial estimate of the chemical composition of an unknown body, based only on the qualitative appearance of its spectrum. The greater mass and low velocity of reentry vehicles result in the greater prominence of molecular bands in their spectra when compared to meteor spectra. A great variety in the chemical composition of different components in the reentry objects produces considerable diversity in the observed band systems. As noted by Millman (1968), 54 band systems of 27 different molecules were identified in a study of 41 reentries that took place in the period 1960 to 1964.

In any general treatment of the physics of solid objects moving at high speed through the Earth's upper atmosphere the reentry data give us an important extrapolation of the meteor data toward more massive objects and lower velocities. It is hoped that, in the future, a photometric analysis of these spectrographic records will become available.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge useful discussions with Marilyn L. Bankoff, Richard M. Carbone and Charles C. Petty at the Avco Everett Laboratory, Everett, Mass., and with the late Luise Herzberg at the Defence Research Board, Ottawa, Ont.

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