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Fall, recovery and description of the Coleman chondrite

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(Dedicated to the memory of Paul Pellas)

Abstract–A 0.5 kg stony meteorite associated with a bright bolide seen over southeastern Michigan on 1994 October 20 has been recovered. The circumstances of the fall and recovery of this chondrite, named Coleman, are presented. The most likely trajectory from the observations of the event implies preatmospheric orbital parameters typical of meteorites. Gamma-ray spectrometry of the cosmogenic radionuclides showed that the recovered mass was an interior fragment of a larger body and revealed abnormally high ^{22}Na and ^{26}Al activity. Electron microprobe analysis yielded compositions of $Fa_{24.1}$ and $Fs_{20.3}$, which are consistent with an L-chondrite classification. Petrographically, the presence of chondrules, the observed mineralogy and the degree of chondrule-matrix integration suggests assignment to petrologic type 6.

INTRODUCTION

Residents of southeastern Michigan, USA, were startled the night of 1994 October 19–20, by a bright fireball. The bright light that lit the sky was followed by a loud sound that many believed to be an explosion. Police stations, weather bureaus, and other official offices received numerous calls from concerned citizens.

One of those awakened by the sound was Tom Hagon of Coleman, Michigan, who next heard something hit his house. The following morning he discovered a hole in the roof, from which he recovered a blackened stone that was later identified as a meteorite. This paper describes the circumstances of this fall and presents the results of initial studies of the meteorite.

THE FALL AND RECOVERY

The bolide appeared about 1:52 A.M. Eastern Daylight Time (5:52 UT) and was seen in the eastern half of the Michigan's lower peninsula from Oakland and Jackson Counties in the south to Roscommon County in the north. The light was sufficiently bright to attract the attention of those awake at this hour. This light was followed by a noise loud enough to awaken those asleep and rattle windows. Given the exceptional brightness and loudness of the associated sound, the first author (an astronomer) reported the event to the astronomical community and began to gather reports from witnesses for possible use in determining a trajectory and/or locating a fall.

Mr. Tom Hagon was asleep at his home located near Coleman, Michigan, USA (84°30' 28" W, 43°45' 40" N, 216 m) when the fireball occurred. Awakened by the barking of his dog, he first heard a sound like thunder and then heard something hit his house. A quick inspection in the dark revealed nothing, but in the morning he discovered a hole ~10 cm in diameter in the roof. In the hole, resting on a ceiling support beam, was a black stone. The object had penetrated the ~1 cm thick roof consisting of two layers of rolled roofing material, a piece of sheet metal and a 1/4 in (0.4 cm) thick plywood board. Hagon estimated from the shape of the hole and the location of the stone that it had come from the south at an ~80° angle to the ground.

Hagon, a high-school custodian, patched the hole before reporting to work. At the suggestion of coworkers, he contacted Central Michigan University (CMU) about identifying the object as a meteorite. He was put in touch with the first author who, learning the circumstances of the recovery and a general description of the stone, drove to Coleman High School to examine it.

The black, ablated fusion crust was strong evidence that the object was indeed a meteorite (see Fig. 1). A mass of 469 g was measured using a balance at the high school. The density, lack of strong magnetism and visual appearance of the interior exposed by a small chip in the crust showed that it was not an iron. Hagon's home was

FIG. 1. Mr. Tom Hagon holding the meteorite he recovered. Photographed by Michael Hollenbeck, *The Saginaw News*.

visited to examine the hole in the roof, but a thick layer of roofing tar used for the patch filled the hole and precluded measurements. No other objects were found around the Hagon home. Other searches were made in the Coleman area over the next several weeks in response to reports of unusual noises the night of the fireball, but these, as well as news articles requesting information on unusual rocks, did not produce additional recoveries.

INITIAL PROCESSING

Mr. Hagon consented to scientific study of the meteorite and brought it to the CMU campus on October 27. It was examined by the second author (a geologist) who concurred that the object was a stony meteorite. Iron sulfides, plagioclase feldspar and olivine were identified with a hand magnifier. Experts in the field suggested that the initial study should be nondestructive gamma-ray counting of cosmogenic radionuclides. Detection and quantification of the short-lived isotopes depends critically on the time elapsed since the fall. Thus, the meteorite was photographed, weighed and several small flakes scraped from the exposed interior with a stainless-steel dental tool, after which it was packaged and sent by air express to the Pacific Northwest Laboratories (PNL), Washington, for counting. The stone arrived there on October 28 and was returned to Michigan on November 14. On return, it was carefully measured and rephotographed and then, at the owner's request, returned to him uncut on December 2.

The meteorite was again brought to CMU on 1995 January 10 to allow removal of a study specimen. A two day attempt to dry cut the stone with a diamond hand saw was eventually abandoned, and a section was cut from the base using a low-velocity rotary diamond saw employing methanol as the coolant. The cut face of the main mass was polished, examined and photographed and the resulting 292 g portion was then returned to Mr. Hagon. It was eventually sold to a private collector.

The portion removed for later study and preparation of thin sections initially weighed 147 g. This sample was sent to the NASA Meteorite Processing Laboratory at Johnson Space Center where three 1 in (2.5 cm) diameter polished thin sections were prepared and a 34 g specimen removed. These were returned to CMU along with ~22 g of powder from the cutting and the remaining stone (~85 g), which was returned to Mr. Hagon.

ASSOCIATION WITH THE OCTOBER 20 FIREBALL

The circumstances of the recovery strongly suggest that the meteorite was associated with the bolide seen the previous night, but the possibility exists that the two events were not related. Eyewitness reports of the meteor from across the state were collected in order to determine an approximate trajectory. Twelve reports were gathered by the authors from the mid-Michigan area, which were supplemented by 38 reports from the southern part of the state collected by R. Victor of Michigan State University's Abrams Planetarium and one report on file in the International Meteor Organization fireball data base. The observations initially seemed completely inconsistent, with some observers reporting the meteor moving toward the west, others toward the north, and still others toward the east. A careful review of the reports, which are summarized in the appendix, allowed the apparent inconsistencies to be resolved.

First, the reports show that two fireballs were observed the night of 1994 October 19–20: the event described above and an earlier one at 10:20 P.M. EDT (2:20 UT). The observers of the earlier event were in agreement that it traveled roughly southwest across the southwestern portion of the state with a descent angle of ~60°. The reports of the 5:52 UT event suggested an approximate magnitude of −11 and showed perspective effects that defined a path in a roughly northeast direction with a fairly steep angle of descent. The object was observed to change color along the flight path and finally disintegrate into three major fragments, each of which was luminous. The reported brightness and fragmentation are consistent with the gamma-ray counting results for ^{56}Co and ^{60}Co, which indicate that the recovered stone was a nonsurface fragment of a larger meteoroid. Together, the observations show with reasonable certainty that the recovered meteorite was indeed associated with the 1994 October 20 5:52 UT fireball. Thus, it becomes the third documented fall in Michigan. The name "Coleman" has been proposed and accepted (Grossman, 1996). Other fragments not yet recovered likely exist.

ATMOSPHERIC TRAJECTORY AND ORBIT

The most reliable and useful eyewitness reports have been used to find the most likely atmospheric trajectory and the associated orbital solution. Unfortunately, only five observers provided quantitative measures of altitude and/or azimuth. Furthermore, the observers were not well distributed about the path, with almost all to the south and east. There were several estimates of the delay between the visual event and the acoustics, which help constrain the path, but we could not locate any photographic, satellite or seismic station records that might permit a velocity determination.

Given the poor data set and the inherent uncertainties of visual observations, the trajectory solution is very uncertain. The best fit solution yields an arrival azimuth of 195° ± 10° with a slope of 45° ± 15°. The slope, however, is essentially determined by just two observations and our adopted error is little more than a guess based on the approximate duration estimates, locations of the observers and the comparison of the trajectory endpoint to the meteorite recovery location. This trajectory implies that the meteor became visible at a height of 60 km over Hubbardston, Michigan, lasted about three to four seconds, and then fragmented at ~20 km above a point 9 km south-southwest of where the meteorite was found. The locations of those providing observations and the computed ground path of the meteor are shown in Fig. 2. Filled symbols indicate reports used in determining the trajectory, while the different shapes identify reported noise associated with the event. The locations where sound was heard support the computed trajectory.

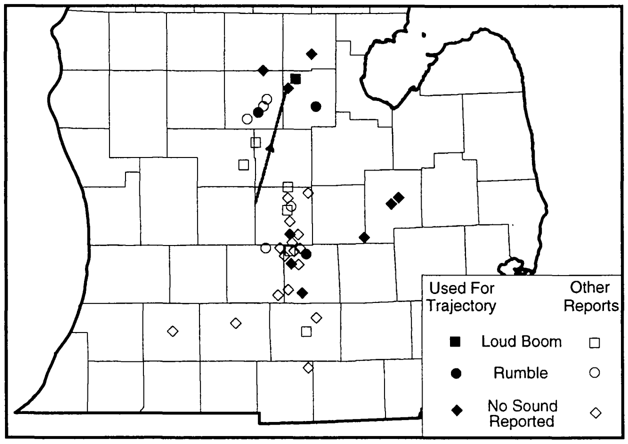

FIG. 2. Map of Michigan's lower peninsula showing the locations of the eyewitness reports and the computed ground track. Filled symbols identify the reports used in determining the trajectory. Symbol shapes indicate where noise was heard: box = loud boom, circle = a rumble, diamond = no noise reported.

The orbital parameters for the meteoroid that result from the adopted trajectory show that the inclination was low, certainly <10° and probably <5°. Under the assumption that aphelion was between the orbits or Mars and Jupiter, as is the case for all four meteorites with accurate preatmospheric orbits (Brown *et al.,* 1994 and references therein), the perihelion distance was in the range 0.7–0.9 AU. The collision probably occurred at the ascending node before perihelion, with an entry velocity of between 13 and 21 km/s. The orbital parameters are typical for meteorites (Wetherill and Revelle, 1981).

The predicted maximum for the Orionids in 1994 was October 22 at 6 UT (Hawkes, 1994), and it is natural to question if the meteor could be part of this shower that is associated with Halley's Comet. The adopted trajectory projects to $\alpha = 1^h40^m$, $\delta = -5°$, which differs significantly from the Orionid radiant of 6^h22^m, +16°; the Orionid entry velocity of 66 km/s is incompatible with the eyewitness accounts of brightness and duration. As expected, the meteor was not an Orionid.

DESCRIPTION AND PHYSICAL PROPERTIES

A general view of the uncut meteorite is shown in Fig. 3. On recovery, it was completely covered with a black fusion crust with the exception of two small chips that were apparently lost during impact; neither was subsequently found. The uncut stone weighed 469.0 ± 0.1 g as measured initially at Coleman High School and later at CMU. The small size of the chips, roughly 15 × 9 mm and 5 × 3 mm, indicates that the mass before impact was only slightly larger.

The meteorite had a maximum length of 9 cm and a maximum transverse dimension of 8.5 cm. The shape was an irregular tetrahedral pyramid with a quasi-round base. The three upper faces were relatively flat triangles that intersected at angles of 50°, 60° and 70° and inclined at 60° to 80° from their intersection with the base. Each face widened from the point of ternary intersection toward the base. The largest face was 8 cm from point to base and had a basal width of 8.5 cm.

The base of the stone appeared on first impression to be round but on inspection was seen also to be composed of three faces that intersected at angles of ~40°, 60° and 80°. These faces were inclined from the plane defined by the widest cross section at ~30°. The edges formed by the intersections of the basal faces were rotated ~30° with the edges formed by the upper pyramid.

The upper faces were characterized by flight markings including "thumb prints" (piezoglyphs) and congealed thin streams of melted ablated material forming a portion of the fusion crust (see Fig. 4). The base of the stone had no piezoglyphs or congealed streams. This, along with the general shape, indicate flight with the base forward, and the meteorite was recovered from the hole in the roof in this orientation.

The base portion of the fusion crust turned slightly red-brown in the week between the recovery and the initial examination at CMU; this color change had advanced noticeably by the object's return from PNL three weeks after recovery, but there was little further change up to the time it was cut eight weeks later. The upper portion of the crust retained its original black coloring.

Examination with a hand magnifier revealed that the fusion crust had a thickness of 0.4 mm. The interior of the sample, visible where chips had been removed during impact, was characterized by whitish silicate minerals interspersed with small (0.1 mm) metallic grains. Energy dispersive electron microprobe analysis of several small flakes scraped from the exposed interior indicated the presence of Mg-rich olivines and orthopyroxenes, sodic plagioclase feldspar and iron sulfides. The attraction of the stone to a hand magnet was compared to that of an iron meteorite (Canyon Diablo) and to a H5 chondrite (Plainview). The attraction was estimated at half that of the chondrite and one-quarter that of the iron, which suggested an L-chondrite classification. A bulk density of 3.06 g/cm^3 was determined by displacement in methanol.

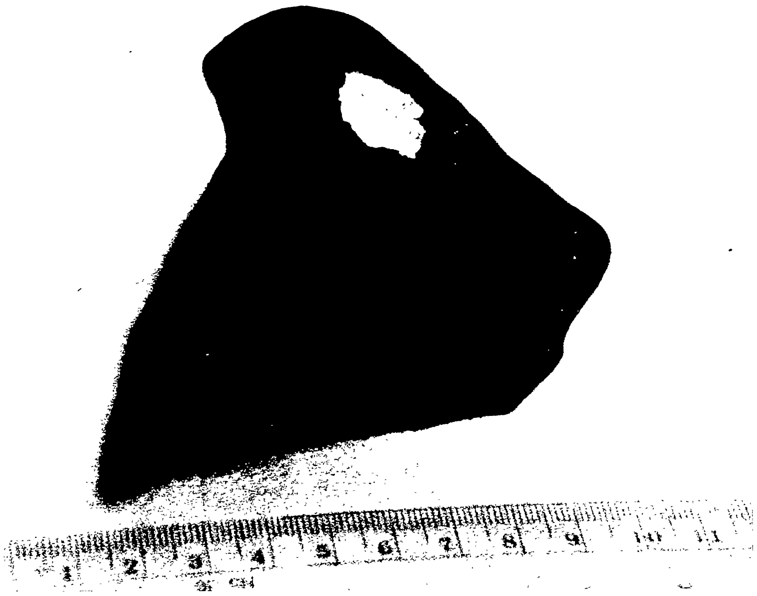

FIG. 3. View of the uncut meteorite showing the shape and the largest chip. A centimeter ruler is shown for scale.

FIG. 4. View of the meteorite showing pyramidal shape with base and congealed stream markings.

GAMMA-RAY SPECTROMETRY

Cosmogenic nuclides contain valuable information that can reveal the recent history of a meteorite on timescales ranging from the past few weeks (*e.g.*, using ^{48}V, $t_{1/2} = 16$ d) to the past few million years (*e.g.*, using ^{26}Al, $t_{1/2} = 740$ ka). Such information can be used to determine cosmic-ray exposure ages, terrestrial residence times, effects due to multistage exposures and variations in the cosmic-ray flux.

The recovered piece of Coleman (0.469 kg) was received in Richland, Washington on 1994 October 28, approximately nine days after it fell. Counting began on 1994 October 28 at 5:26 P.M. (PST) and was completed on 1994 November 2. The sample was counted for five 24 h counting periods, for a total of 6880 min, to assay for various short- and long-lived cosmogenic radionuclides: ^{22}Na, ^{26}Al, ^{46}Sc, ^{48}V, ^{54}Mn, ^{56}Co and ^{60}Co. All of the counting was done using a high-efficiency NaI(Tl) multiparameter gamma spectrometer. This detector uses two 30 cm diameter × 20 cm thick NaI(Tl) crystals for coincidence detection of multiple gamma-rays, which leads to a large reduction in background and interferences caused by other radionuclides, cosmic rays and detector noise. Further details on this instrument are given by Brodzinski (1973), Perkins *et al.* (1970), Wogman *et al.* (1967, 1970), Reeves *et al.* (1984) and Miley *et al.* (1992).

Calibration procedures for ^{26}Al were the same as those used for the analysis of Antarctic meteorites (Edwards *et al.*, 1982; Evans and Reeves, 1987), which uses a calibration curve based on our extensive library of mockups of freshly fallen meteorites. For ^{22}Na and ^{60}Co, a series of mockups (five for each isotope) were used to calibrate the instrument in a fashion similar to that used for ^{26}Al. For the other radionuclides, a combination of procedures was used. Calibration data were obtained by measuring existing mockups containing ^{22}Na and ^{60}Co and by using data from earlier freshly fallen meteorites that were measured on the same instruments. This procedure, although less accurate, avoided the expense of fabricating new mockups for the short-lived isotopes, as was done in the past. These procedures resulted in data that are accurate to 5–10% for ^{26}Al, 10–15% for ^{22}Na and ^{60}Co, and ~25% for the other isotopes, excepting those with low signal to noise.

The following radionuclides were detected in Coleman: ^{22}Na ($t_{1/2}$ 2.6 a), ^{26}Al ($t_{1/2}$ 740 ka), ^{46}Sc ($t_{1/2}$ 84 d), ^{48}V ($t_{1/2}$ 16 d), ^{54}Mn ($t_{1/2}$ 312 d), ^{56}Co ($t_{1/2}$ 77 d) and ^{60}Co ($t_{1/2}$ 5.3 a), along with ^{40}K. The results are given in Table 1. The ^{26}Al and ^{22}Na activities in the Coleman specimen are higher than the typical range for an L-chondrite, for which normal values fall near 59 ± 9 dpm/kg for ^{26}Al (Evans and Reeves, 1987) and 60–110 dpm/kg for ^{22}Na (Evans *et al.*, 1982). Coleman fell about three years past the most recent solar maximum in 1991, during which the ^{22}Na production rate should have been at a level intermediate between the minimum and maximum levels due to solar modulation of the galactic cosmic-ray flux. Past results (Evans *et al.*, 1982) show that L-chondrites that fell during the 1969 solar maximum had ^{22}Na activities in the range of 60–80 dpm/kg; whereas, those falling during the 1976 solar minimum had activities in the range of 80–110 dpm/kg. The Coleman ^{22}Na activity falls above the normal range, which indicates a possible abnormal cosmic-ray exposure history.

TABLE 1. Radionuclides in Coleman.

Isotope	Coleman* (dpm/kg)	Chondritic Range† (dpm/kg)
^{22}Na	111 ± 11	60 – 110
^{26}Al	77 ± 4	59 ± 9
^{46}Sc	10 ± 2	5 – 15
^{48}V	12 ± 3	15 – 40
^{54}Mn	122 ± 30	50 – 110
^{56}Co	4 ± 1	5 – 15
^{60}Co	10 ± 1	<1 to >100

*Data corrected to time of fall: 1994 October 20, 5:52 UT.
†Evans *et al.* (1982), Evans and Reeves (1987).

The ^{60}Co results can be used to determine the size of the preatmospheric body. The ^{60}Co activity indicates that the original preatmospheric mass of Coleman was in the 10 to 100 kg range, based on comparison with other falls and from model results (Eberhardt *et al.*, 1963; Spergel *et al.*, 1982). The low ^{56}Co activity indicates no significant exposure to solar cosmic rays and confirms a preatmospheric body that is much larger than the recovered specimen (Evans *et al.*, 1987; Nishiizumi *et al.*, 1990), which is consistent with the ^{60}Co results. For comparison, the ^{60}Co activities of Bruderheim (L6, 303 kg) and Dhajala (H4, 45 kg) are 9 ± 1 and 6 to 14 dpm/kg. Larger meteorites, such as Jilin (H5, ≥4000 kg) and Allende (CV3, ≥2000 kg) have ^{60}Co activities in the ranges of 55–215 and 23–179 dpm/kg (Honda *et al.*, 1961; Evans *et al.*, 1982).

PETROGRAPHIC DESCRIPTION AND CLASSIFICATION

Macroscopically, the interior (Fig. 5) is composed of light gray stony material with small metallic grains interspersed throughout and is transected by distinct and abundant black shock veining. A few indistinct chondrules are observable in hand sample.

Petrographic observations and energy dispersive electron microprobe analyses of thin sections disclosed the presence of several silicate phases (olivine, ortho- and clinopyroxene, and minor sodic plagioclase), Fe-Ni alloys and Fe-sulfides, all of which are common constituents of ordinary chondrites. Modal analysis (2736 points) of two thin sections showed that the silicate matrix, mineral fragments and chondrules comprise ~84% of the sample, opaque primary Fe-Ni alloys and Fe-sulfides ~14% with the remaining 2% consisting of opaque shock veins.

Slightly more than 4% of our specimen consists of recognizable chondrules or chondrule fragments. Barred olivine chondrules (Fig. 6) dominate, and these are slightly more than twice as abundant as radial pyroxene chondrules. The mesostasis glass within the barred olivine chondrules is completely recrystallized (Fig. 7). The boundaries between chondrules and the matrix are indistinct and difficult to define. Granular olivine chondrules, monomineralic olivine crystals and their fragments may be present but fragmentation and thermal metamorphism obscure their margins and render them essentially indistinguishable from the surrounding silicate matrix. Many individual features can be traced across shock veins, commonly with a few millimeters displacement along the vein (Fig. 8), which suggests that the fragments constituting the stone are all derived from a single rock and not a mixture of unrelated fragments. Thus, the brecciation is predominately shock brecciation. However, the possibility of polymict brecciation (*e.g.*, the mixing of compositionally distinct but petrographically similar ordinary-chondrite fragments) cannot be ruled out. The presence of chondrules, the overall texture and the observed mineralogy confirm the meteorite to be an ordinary chondrite. The observed modal content of opaque minerals is consistent with membership in either the H- or L-chondrite groups. The degree of chondrule-matrix integration suggests assignment to petrologic type 6.

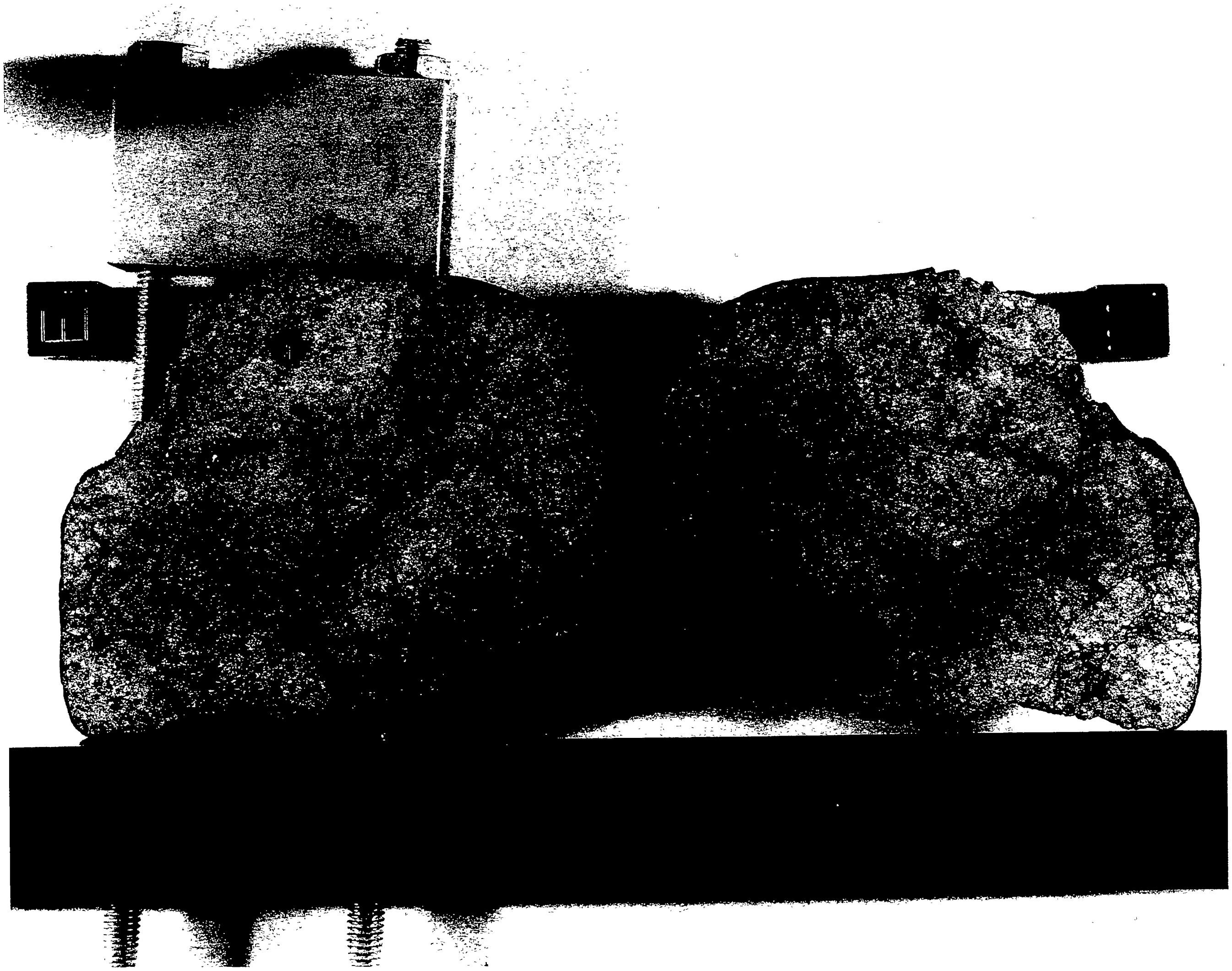

FIG. 5. View of the cut meteorite showing the interior. Photograph by NASA Meteoritic Processing Laboratory.

Quantitative wavelength dispersive analyses of olivine, orthopyroxene and plagioclase utilizing CMU's ARL-SEMQ electron microprobe were performed. Operating conditions of 110 mA emission current, 15 kV accelerating potential, 10 μA sample current /10 μm spot size for plagioclase and 15 μA sample current /2 μm spot size for olivine and pyroxene were employed. Counting times of 10–30 s were common using LiF, PET and TAP crystal spectrometers. Well-characterized, homogeneous, natural mineral standards similar in composition to the unknown phases were used. Several grains of each mineral from different brecciated fragments within the thin section were analyzed. The averaged analytical results and associated mole fractions are given in Table 2a,b; 1σ errors appear in parentheses.

The derived compositions of olivines ($Fa_{24.1\ \pm\ 0.4}$) and orthopyroxenes ($Fs_{20.3\ \pm\ 0.3}$) in the sample are consistent with those commonly reported for L-chondrites (Dodd, 1981). These results differ from those reported for another sample by Sipiera and Kanachi (see Grossman, 1996), who classified Coleman as an LL5-chondrite on the basis of the reported Fa and Fs mole fractions. While the possibility of a polymict breccia exists, which would explain the discrepancy, our analysis of grains from different breccia fragments produced relatively homogenous and highly stoichiometric results that remained consistent with an L-chondrite classification. Our averaged analyses of plagioclase grains within the sample produced stoichiometric results corresponding to $Ab_{84.4\ \pm\ 0.2}\ An_{10.0\ \pm\ 0.4}\ Or_{5.6\ \pm\ 0.5}$. These data are essentially identical to the typical composition of plagioclase ($Ab_{84}\ An_{10}Or_{6}$) reported for L6 chondrites by VanSchmus and Ribbe (1968). Taken together, the petrographic observations and chemical analysis indicate classification as an L6 chondrite, veined (shocked).

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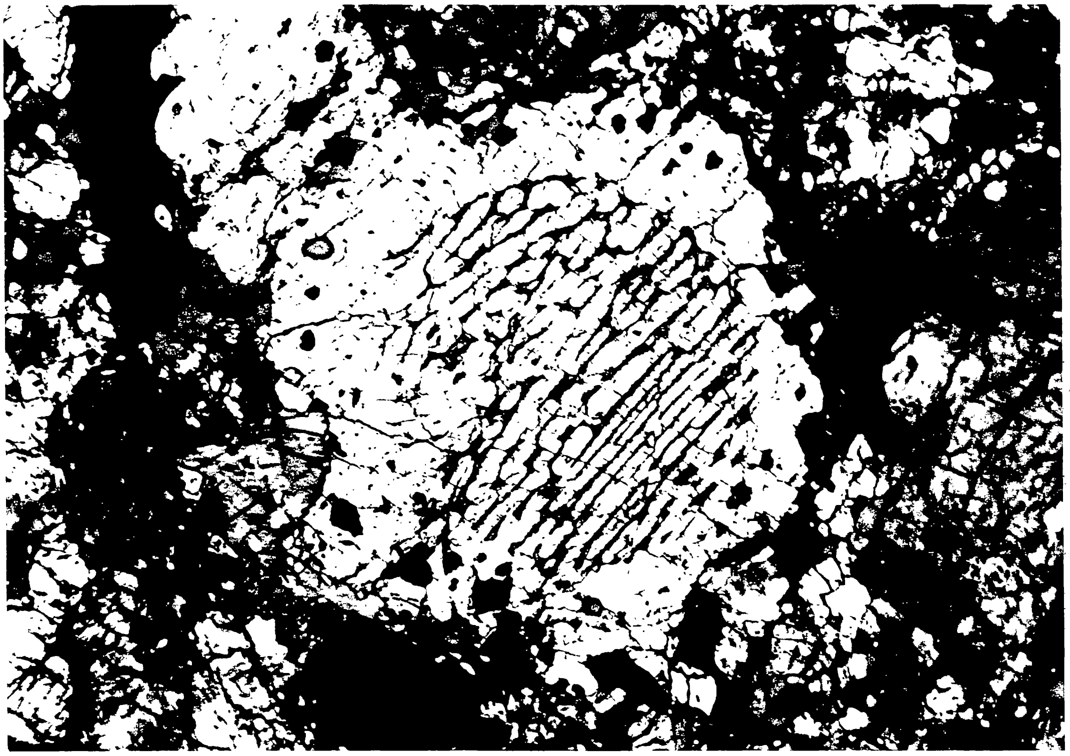

FIG. 6. A barred olivine chondrule. Note the indistinct boundary between the chondrule and the matrix (a high degree of chondrule-matrix integration). Crossed polarized light with gypsum plate. Field of view is 1.0 × 1.4 mm.

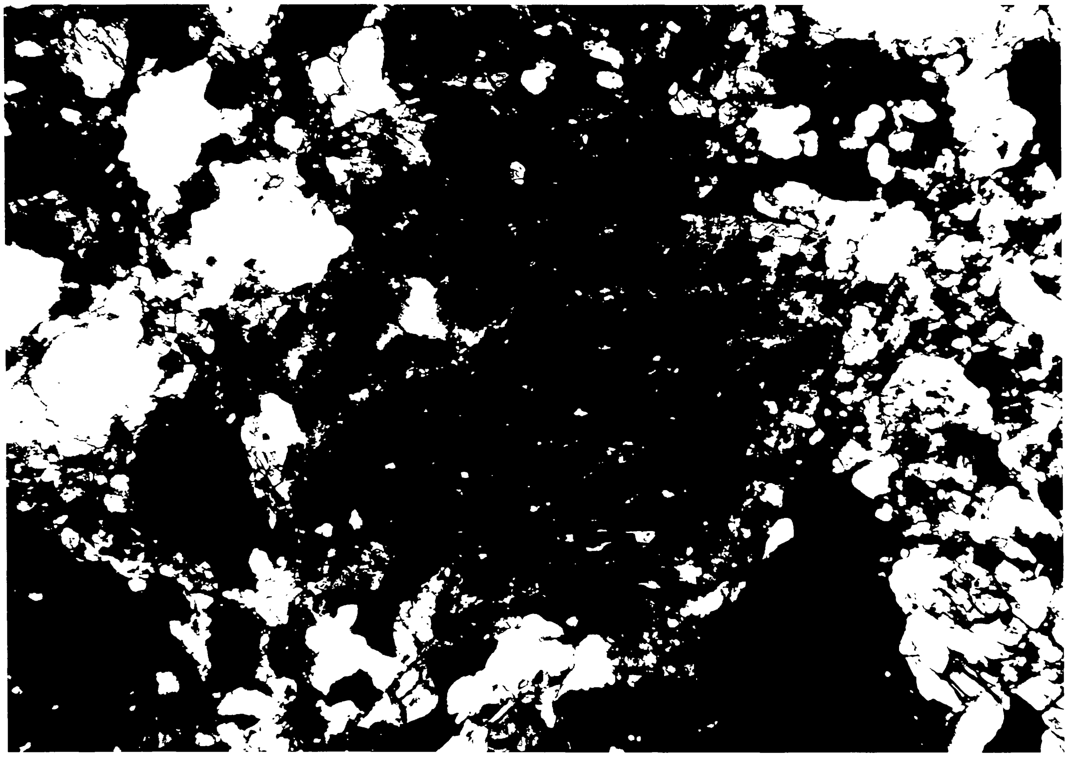

FIG. 7. Devitrified mesostasis within a chondrule. Same chondrule and field of view as in Fig. 6 but in cross-polarized light without gypsum plate and with chondrule bars rotated to optical extinction. Visibly birefringent material between chondrule bars indicates complete recrystallization (devitrification) of mesostasis. Again, note the high degree of chondrule-matrix integration. Field of view is 1.0 × 1.4 mm.

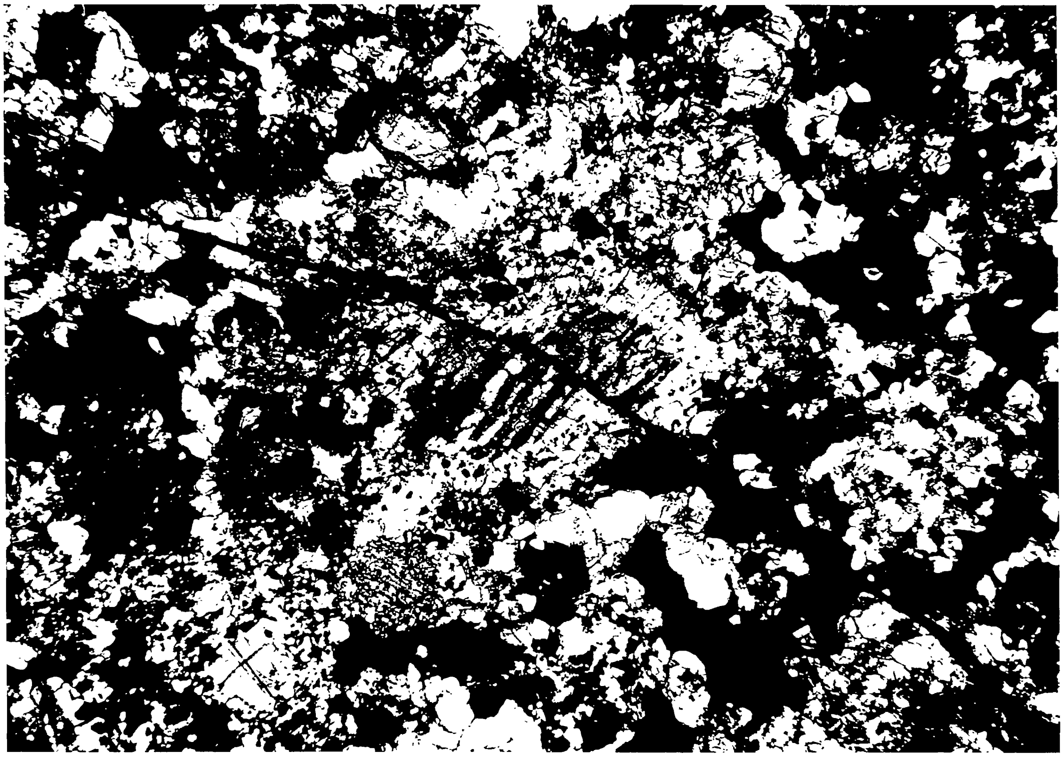

FIG. 8. Feature displacement along a shock vein. The chondrule in the center of the picture can be traced across the vein but exhibits ~0.2 mm right-lateral displacement along the vein. Field of view is 2.5 × 3.5 mm.

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TABLE 2a. Microprobe analysis.

	Olivine	Orthopyroxene	Plagioclase
# grains	4	3	2
# spots	24	12	10
SiO_2	37.9 (8)	55.4 (5)	65.4 (11)
Al_2O_3	0.01 (1)	0.16 (1)	20.7 (2)
ΣFe as FeO	22.0 (5)	13.4 (2)	
ΣFe as Fe_2O_3			0.4 (2)
MgO	38.8 (9)	28.9 (6)	
MnO	0.45 (3)	0.48 (1)	
CaO	0.02 (1)	0.92 (2)	2.1 (1)
Cr_2O_3		0.12 (2)	
Na_2O		0.01 (1)	9.8 (2)
TiO_2		0.18 (1)	
K_2O			1.0 (1)
BaO			n.d.
Total	99.2	99.6	99.4

TABLE 2b. Microprobe analysis.

	Olivine	Orthopyroxene	Plagioclase
Normalized to	3 cations	4 cations	5 cations
Si	0.992	1.987	2.903
Al	0.0002	0.007	1.083
Fe^{2+}	0.482	0.402	
Fe^{3+}		0.013	
Mg	1.516	1.545	
Mn	0.010	0.015	
Ca	0.001	0.035	0.100
Cr	0.003		
Na	0.001	0.844	
Ti	0.005		
K		0.056	
Ba		0.000	
ΣOxygens	3.992	5.997	8.002
Fe/(Fe + Mg)	0.241	0.206	
Fa/Fo(%)	24.1/75.9		
Wo/En/Fs (%)	1.8/77.9/20.3		
Ab/An/Or/Cs (%)	84.4/10.0/5.6/0.0		

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APPENDIX

The following three tables give summaries of the eyewitness reports of the fireball observations on the night of 1994 October 20–21. Table A1 contains those reports providing information of use in determining the trajectory of the recovered meteorite. Table A2 contains the reports that mentioned noise or color. Table A3 contains the reports that refer to the earlier fireball at 2:20 UT.

The entries attempt to reproduce the actual words of the observers. Kreymer's report was obtained from the International Meteor Organization fireball database (http://www.imo.net). The reports of Chapman, Ehnis, Hagon, Harper, Hude, McLemore, Price, Simon and Walden were collected by the authors. The remainder were collected by Robert Victor (Abrams Planetarium, East Lansing, Michigan) with follow-up interviews with Brown, Hunter, Klassen, Miskowski, and Smith by Osborn. The geographic coordinates were determined by the authors from topographic maps.

TABLE A1. Reports of the meteor used in determining its trajectory.

Observer (Time observed)	Long. (West)	Lat. (North)	Positional information	Other information
Jack Harper (about 1:45 A.M.)	84°21'57" ±8	43°55'00" ±150	Viewed object ~30° south of due west, very high above horizon; was below the clouds.	A colleague north of highway M61 saw it to the south.
Al Price (not reported)	84°45'55" ±25	43°49'15" ±35	Almost straight up; a little south and east.	
Tom Hagon (2:00 A.M.)	84°30'28" ±2	43°45'40" ±2	Fragment recovered at this location.	
Elizabeth Simon (not reported)	84°31'30" ±15	43°44'06" ±12	Direction of travel north-northeast; burned out just overhead.	
David Chapman (at 1:51 or 1:56 A.M.)	84°20'10" ±60	43°36'17" ±10	Light cast faint shadows; light from north-northwest; long rumbling sound 45–60 s later.	Light lasted 2–3 s.
Doug McLemore (not reported)	84°47'03" ±5	43°35'03" ±5	Direction of travel west-southwest to east-northeast and almost overhead; sound ~1 min later.	Was above clouds (backlit them).
Paul Smith (1:52 A.M. precisely)	83°41'00" ±50	43°02'10" ±15	In west-northwest moving down at 10° CCW to vertical; beginning altitude 55–60° up, ending <10° up behind trees.	Lasted ~3 s; bright as full Moon but smaller.
Ken Hude (not reported)	84°32'36" ±7	42°49'50" ±35	Descending at 10° CCW to vertical with projected impact at azimuth 5°, altitude 0°.	
Mark Brown (not reported)	83°56'10" ±20	42°49'00" ±10	Descending at ~30° CCW to vertical; azimuth from ~340° to 0°.	Duration ~1 s.
Dwayne Hannah (about 2:00 A.M.)	84°32'02" ±12	42°39'16" ±12	Moving upper left to lower right; disappeared in north-northeast.	
Rich Miskowski (1:52 A.M.)	84°26'48" ±5	42°28'47" ±15	Descended at 10° CCW to vertical; beginning at azimuth 350°, altitude 30°; ending at azimuth 10°, altitude 0°.	
Nicky Perkins (about 2:00 A.M.)	84°25'00" ±60	42°42'54" ±36		Sound like distant thunder a few seconds after light, then again 7–8 min later.
A. Kreymer (1:51 A.M.)	83°40'00"	43°03'00"	Began at $\alpha = 319°$, $\delta = +37°$, ended at $\alpha = 290°$, $\delta = +42°$	Duration 2 s, velocity 10°/s.

TABLE A2. Reports of the meteor that mentioned noise, color or other features.

Location (EDT)	Long. (West)	Lat. (North)	Reported noise	Reported color, brightness or other comments
Coleman (2:00 A.M.)	84°30.5'	43°45.7'	Sonic boom, then loud rumble	
Coleman	84°31.5'	43°44.1'	(no report)	Streak of fire, white-orange trail.
Sanford (about 1:45)	84°22.0'	43°55'	(no report)	Saw it explode into a half dozen fragments.
Clare	84°45.9'	43°49.3'	(no report)	Like lightning at first, then broke into three yellow colored pieces.
Mt. Pleasant (1:30)	84°46'	43°37'	Thunder sound	White-yellow.
Mt. Pleasant	84°47.1'	43°35.1'	Sound ~1 min after light	Fast bright light above clouds.
Mt. Pleasant	84°46'	43°36'	Rumbling	(Did not see object.)
Winn	84°54'	43°31.5'	Loud rumble 4 min after light	Bright yellow object in southwest sky moving northerly (taken from newspaper report).
Midland (1:51 or 1:56)	84°20.2'	43°36.3'	Long rumbling 45–60 s after light	Clouds pulsed with light sufficient to produce shadows weaker than from moonlight.
Elwell (just before 2:00)	84°50'	43°23'	Like an explosion	
Crystal Lake (1:50–2:00)	84°56'	43°15.5'	Huge boom	Only saw a bright light from object.
N of St Johns (1:52 A.M.)	84°33.9'	43°07'	Loud boom	All white, brighter around outside.
Elsie (1:57 A.M.)	84°23.8'	43°05'	None	Red head; white trail; moved south to north.
N of St. Johns	84°33.9'	43°03'	None	Whole sky lit up.
St. Johns (about 2:00)	84°33	43°01'	Boom 45 s after light	Flash of red, then green, moved southeast to north.
St. Johns (1:58)	84°33.5'	43°00'	Like clap of thunder	
S of St. Johns (2:00)	84°32.8'	42°55'	None	Green-orange head; white tail.
DeWitt (about 2:00)	84°29.1'	42°50.5'	(no report)	Bluish white flashes, a big streak heading northeast.
DeWitt	84°32.6'	42°49.8'	(no report)	Flashed and pulsated like heat lightning.
DeWitt (1:30–2:00)	84°32'	42°47'	(no report)	Bright bluish white; flickering light from north.
Lansing	84°38.5'	42°45'	None	Sky lit like lightening, flashing light as went behind clouds; fell to north.
Lansing	84°28'	42°44.9'	None	Yellow red tail, traveling northeast, high up
Lansing (about 2:00)	84°33'	42°44.1'	A boom	White-yellow tail, looked like flashlight; travelling northeast.
Lansing (1:56 A.M.)	84°30.7'	42°44'	None	Gold streak to white flash, slight red color.
Lansing	84°34.5'	42°43'	None	A fireball, going north.
Lansing (1:50)	84°34'	42°43'	None	A white ball; north direction but falling almost straight down.
Grand Ledge	84°45'	42°45'	Booming noise for 1 min	
Okemos (about 2:00)	84°25'	42°42.9'	Like distant thunder	A reddish orange flame.
Lansing (1:57)	84°30'	42°39.3'	None	Red-orange-yellow head, trail of blue.
Lansing (about 2:00)	84°32.0'	42°39.0'	(no report)	Bright orange streak.
E of Eaton Rapids (2:00)	84°33.7'	42°30.5'	None	White; like a large firework, heading northeast at an angle.
Eaton Rpds. (about 2:00)	84°39.5'	42°28'	None	Blue trail, flash when hit; heading northeast.
Leslie (1:52 A.M.)	84°26.8'	42°28.8'	(no report)	While streak moving downward; broke into three pieces; much brighter than full Moon.
Flint (1:52 exactly)	83°41'	43°02.2'	(no report)	Very light flash followed by brighter flash, as bright as the Moon but smaller.
N. Jackson Co. (2:00)	84°20'	42°20.2'	None	Red in front, white in back.
Jackson (1:50)	84°25'	42°15'	Loud noise	Power went out at 1:50 A.M., didn't see meteor.
Somerset Center (2:00)	84°24'	42°02'	None	Greenish-blue, long fire trail; sharp angle heading for Earth.
Marshall (about 2:00)	85°00'	42°18'	(no report)	Turned green; it was bright and lit up the sky.
Kalamazoo (1:50)	85°31.9'	42°15.5'	None	Yellow orange, flare at end; moved quickly down through clouds, travelling west to east.

Table A3 appears on the following page

TABLE A3. Observations of the 10:20 EDT meteor.

Observer (time observed)	Long. (West)	Latitude (North)	Description	Color and other observations	Sound
Christopher Walden (well after dark)	84°45'	43°40'	Descended at ~50° CCW angle; starting at 180° azmimuth, 45° altitude; ending at 200° azimuth, 10° altitude.	Faint red dot turning white and forming tail; trajectory had slight arc centered on horizon.	(No report)
Suzanne Klassen (10:20–11:00 P.M.)	84°48'	42°53'	From north, passing just west of overhead, across western sky toward southwest; disappeared just west of due south ~20° up.	White, bright red, green, then gone; appeared brighter than full Moon.	(No report)
Dale Plunkett (10:21 P.M.)	84°45'	42°47'	Heading down to ground.	A blue streak, turning green.	A small noise
Dona Muller (10:15 P.M.)	84°36.4'	42°47'	Moving from northwest to southwest; toward Grand Ledge area.	Yellow-green trail.	No noise
John Higgins (after 10:00 P.M.)	84°34'	42°44'	Moving southeast, 30° to 40° up.	Bright white; a big flash and then a streak.	No sound
Kristy Rutz (10:24 P.M.)	84°35'	42°40'	To west, 85°–90° to vertical, it lasted 1–2 s.	Blue-green, yellow-orange tail.	(No report)
Michael Diebold (10:?? P.M.)	85°15'	42°35'	Moving from northeast to southwest, 60° up.	Blue-white head, red-orange tail.	Noise
James Ehnis	85°03'	42°25'	In west-southwest at 60° angle of descent (altitude from 45° to 5°).		(No report)
Stan and Mary Hunter (10:00 P.M.)	86°25'	42°05'	Moving almost straight down, from 40° up, 15° to right of road (a 60° azimuth).	White head, orange trail; broke apart at end.	(No report)