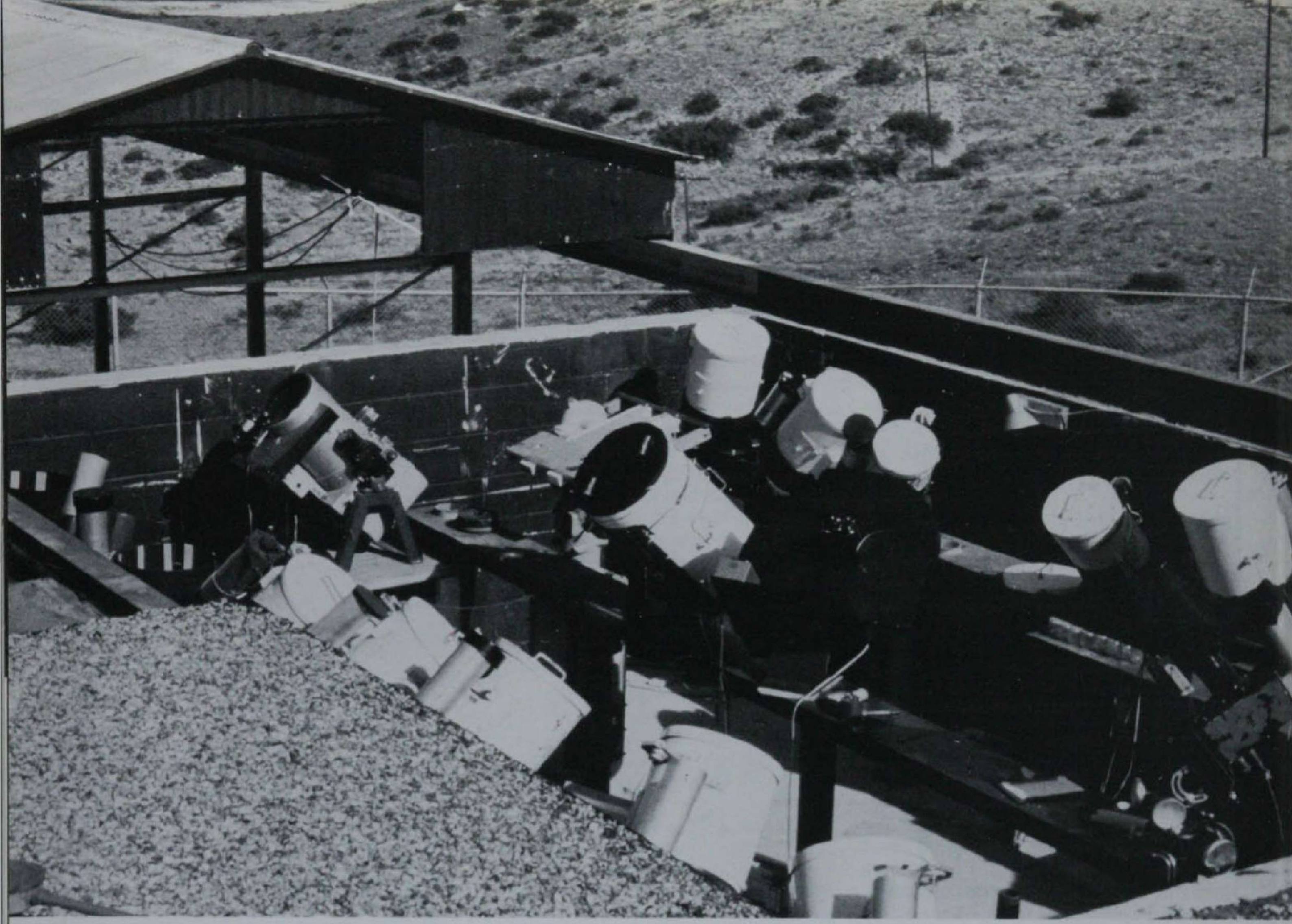

The east room of the NASA-Langley Research Center meteor observatory at Organ Pass, New Mexico, contains this battery of meteor spectrographs that provides almost complete sky coverage above an altitude of 30 degrees. The small tubes on the camera barrels hold photoelectric detectors that open the spectrograph shutters when a meteor appears. This photograph by the author looks toward the southeast, with White Sands Proving Ground in the far distance.

Four Years of Meteor Spectra Patrol

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DURING the initial development of the space program, a major engineering uncertainty was the risk of damage to spacecraft from meteoroids. The Langley Research Center's studies and photographic patrol of meteor spectra were originally part of the NASA program to investigate this potential hazard. These studies were directed toward determining meteoroid masses in the range from 0.001 to 10 grams, for such particles were thought to present the greatest danger.

When a meteoroid enters the earth's upper atmosphere, air resistance causes the body's high kinetic energy to be transformed into heat, which vaporizes the meteoroid and produces a short-lived luminous plasma (ionized gas) that we see as a meteor trail. The radiation emitted by this plasma can be recorded on a spectrogram to be analyzed for meteoroid composition and radiation processes.

To obtain a large sample of meteor spectra in the mass range of interest, an automatic patrol was developed, directed, and supported by the Langley Research Center. The patrol was operated by personnel of the Smithsonian Astrophysical Observatory from 1968 through 1972.

After the immediate aims of the spectral studies were accomplished, the research was redirected to the more basic problem of the relative abundances of the chemical elements in specific meteors and groups of meteors. Our current research is directly concerned with cosmogony (the origin and evolution of the solar system and the universe), and has two primary objectives.

The first is to provide information about the more abundant nonvolatile elements in certain comets, and thus, indirectly, in the early solar-system plasma. Most meteors are produced by material associated with comets, which are generally believed to consist of primordial material whose major nonvolatile elements have not been significantly separated by gravity or melting.

Although the evolution of comets is poorly understood, the association of certain comets with meteoroid streams is firmly established. The chemical composition of the particulate material of comets — the meteoroids — is probably much more representative of the comets than terrestrial surface material is representative of the earth as a whole.

The second objective of this research is to determine typical orbits for different kinds of meteorites, which are meteoroids that survive passage through the atmosphere. Our present understanding of the origin and evolution of the solar system has come mostly from the study of meteorites. Some of them, along with some lunar rocks, are the oldest materials available for laboratory analysis of age, chemical composition, and physical conditions of the primordial solar plasma.

However, the orbits of most meteorites are not accurately determined, since they are deduced from visual observations by untrained observers. Highly precise orbits are known for only two meteorites: Pribram in Czechoslovakia and Lost City in Oklahoma (SKY AND TELESCOPE, March, 1970, page 154). This was because quite complete photographic observations were made as these two meteors passed through the atmosphere. Except for these two, the orbits of meteoroids before capture by the earth are still largely unknown, hence their source within the solar system remains uncertain. It is hoped to determine representative orbits by correlating the chemical compositions of meteors with meteorite compositions, and then relating the latter to the corresponding meteor orbits.

THE PATROL INSTRUMENTS

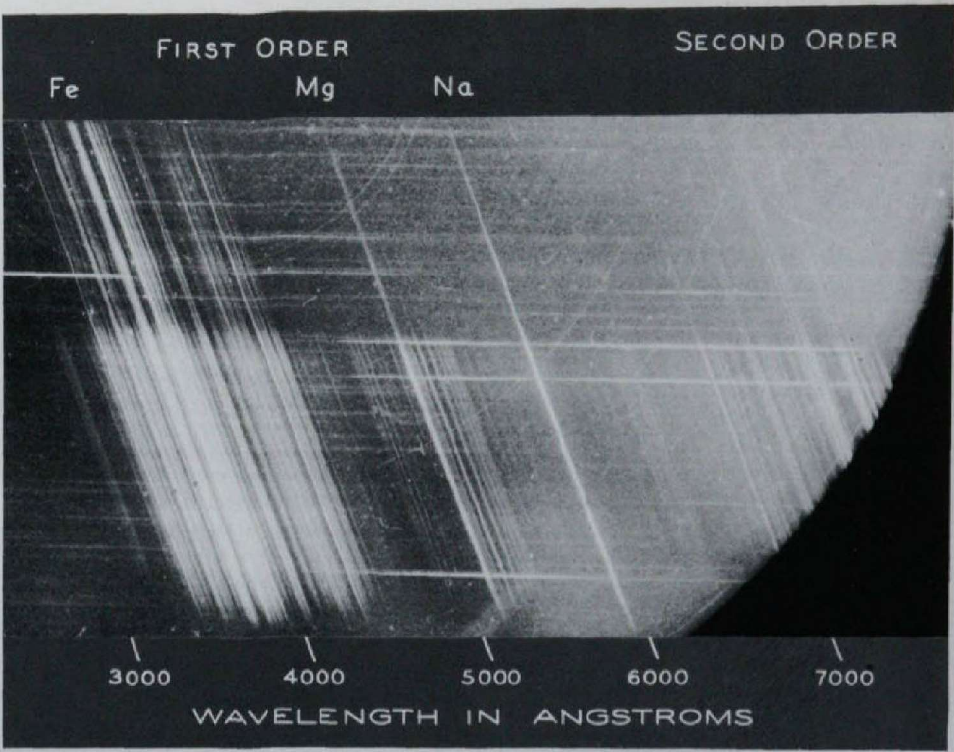
Although the total duration of a meteor is typically one second, the effective exposure time on film is extremely brief, usually less than 0.01 second, because of the image's rapid motion. Hence, a very fast optical system is necessary to record faint meteor spectra. The unpredictability of a meteor's occurrence and sky location requires wide-field optics and long observation times, with attendant problems of discriminating the images from the sky background illumination. However, during the mid-1960's three improvements in optical and photographic technology made possible the recording of meteors 100 times fainter than had been possible with earlier spectrographs.

First, optical-grade fused silica became available at modest cost; this lens material has high transmission in the near-ultraviolet spectral region. Second, large transmission gratings with high blaze efficiency, concentrating the light into selected spectral orders, could be obtained.

Thus, we could set up a battery of 21 Maksutov slitless spectrographs at a fraction of the cost of a single Baker super-Schmidt meteor camera, the previous major instrumental advance in meteor optics. Our spectrographs have apertures of 5, 6, and 8 inches and focal ratios of f/1 and f/1.3. They combine high transmission in the near ultraviolet (where meteor radiation is strongest) with fast optical systems, and make use of the more sensitive extended-red panchromatic emulsion.

The third improvement was a method to avoid plate fogging from background skylight. We incorporated a photoelectric meteor detector that actuated the spectrograph shutter when a meteor occurred in the field. The battery of spectrographs, pictured opposite, and their electronics were built at Langley Research Center.

In the summer of 1968, seven spectrographs and related equipment were taken to New Mexico and placed in routine operation. More units were added over the next 18 months, while special equipment and procedures were developed for cutting, processing, and searching the film and for recording the data. In all, 764 meteor spectra were obtained.



This high-definition spectrum (No. 106 in the NASA-LRC library) of a Taurid meteor was obtained on November 4, 1969. It is representative of most meteors, with iron (Fe) lines dominating the near ultraviolet and blue, magnesium (Mg) the green, and sodium (Na) the yellow. The second-order spectrum at right has twice the dispersion of the first order, originally 123 angstroms per millimeter. Star spectra appear as horizontal streaks.

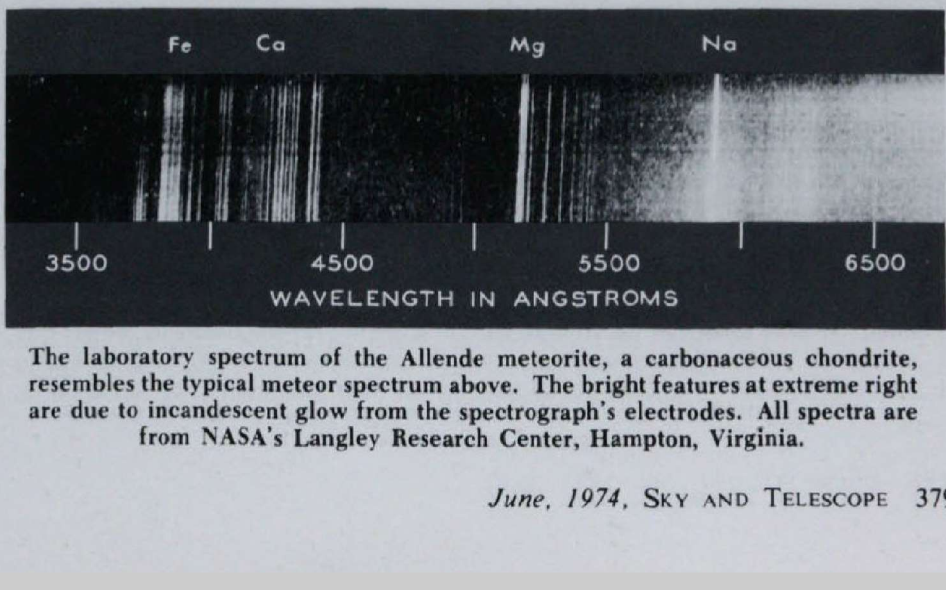
During 1971 and 1972, a pair of direct-photography stations were added to the patrol to obtain meteor trajectory and orbit data. The photographs, which recorded 288 meteors in 1972, were taken with modified K-24 aerial cameras that were equipped with chopping shutters, time displays, and programmers.

OBSERVATIONAL ASPECTS

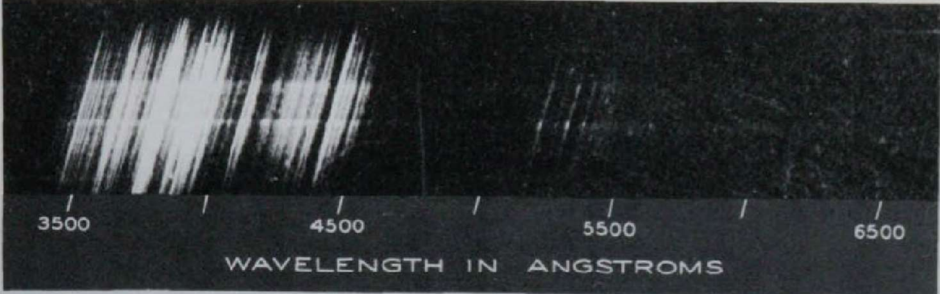
The NASA-LRC faint meteor spectra patrol was operated at a site originally established for the super-Schmidt meteor patrol of the 1950's and later used for Baker-Nunn satellite tracking and laser ranging. It is at Organ Pass, New Mexico, about 12 miles east of Las Cruces, 5,280 feet above sea level and with ready access to U. S. Route 70. The observing station's longitude is 106° 33′ 09″ west, latitude 32° 25′ 24″ north.

This location was chosen primarily for its high percentage of clear nights. The number of useful observing hours is about four times greater than on the East Coast. The dry climate generally favors observing, but dust, high winds, and scattered ultraviolet radiation from lightning in summertime reduce observing efficiency.

An important feature of the patrol was its regular schedule of observations, with nightly operation except for five or six days each month around full moon. The Langley library of meteor spectra — currently the world's largest — contains essentially all of the meteor spectra obtained anywhere dur-



The laboratory spectrum of the Allende meteorite, a carbonaceous chondrite, resembles the typical meteor spectrum above. The bright features at extreme right are due to incandescent glow from the spectrograph's electrodes. All spectra are from NASA's Langley Research Center, Hampton, Virginia.



A nickel-iron meteor produced spectrum No. 432 on January 26, 1971. The absence of a line just short of 6000 angstroms indicates that it was sodium poor. This object was similar in composition to a hexahedrite meteorite.

ing January, February, and March. This is because of the scarcity of meteor showers during this period and the fact that late winter observing conditions are poor in Europe, where another patrol operates regularly.

Statistical Results

The 764 spectra obtained by our patrol can be compared with only 94 known to have been recorded in the United States before 1967. A classification scheme for meteor spectra has been developed by the Canadian astronomer Peter M. Millman, an early pioneer in meteor spectroscopy. His system is based on the number of features in a spectrum (quality class) and the identification of the strongest features (spectral type).

The NASA-LRC spectra and Millman's classification in 1963 of 259 spectra in the World List are summarized in the tables seen below. In general, all of the spectra are useful for qualitative purposes, but only those of classes *a* and *b* are valuable for studying radiation processes and determining the relative abundances of the chemical elements.

Class	*No. of Features*	*NASA*	*World*
a	More than 49	30	16
b	20 - 49	81	54
c	10 - 19	139	68
d	1 - 9	514	121

Type	*Strongest Features*	*NASA*	*World*
x	Mg or Na	167	82
y	Ionized Ca	13	148
z	Fe or Cr	504	28
w	Not x, y, or z	80	6

The spectral types are shown in the second table. Iron is the major radiating element in most NASA-LRC spectra, whereas those in the World List are mostly dominated by the H and K lines of singly ionized calcium. Strong radiation from this and other ions is an anomalous characteristic of bright, fast meteors. Since the NASA-LRC patrol used superior optical systems, it could record the spectra of much fainter but more typical meteors.

Chemical Composition

As far as the major nonvolatile heavy elements are concerned, the composition of most meteors is similar to the sun's, said to be *undifferentiated* with respect to these elements. This is particularly true of meteors associated with comets, such as the Leonids, Perseids, Taurids (see spectrum No. 106 at the top of page 379), and Giacobinids. This similarity also holds for the Geminids, which are not known to be associated with a comet.

The undifferentiated meteoroids are by weight typically about 30 percent iron, 15 magnesium, 3 nickel, 2 each of calcium and aluminum, and 1 sodium. Most of these elements are probably combined with oxygen in the form of ferro-magnesium silicates such as olivine and pyroxene.

The spectra of these meteors strongly resemble low-excitation laboratory spectra of most chondritic meteorites, such as Allende (Sky and Telescope, May, 1969, page 272), in which iron lines dominate the near-ultraviolet spectral region, magnesium the green, and sodium the yellow.

However, some meteors are strongly differentiated with respect to the major nonvolitile elements. One type of differentiation is evident in the high-definition meteor spectrum No. 432, shown opposite, in which only iron, nickel, manganese, chromium, and cobalt were identified among the 123 lines. The nonmetallic elements have been separated from the original material.

Another type of heavy-element differentiation is revealed by spectrum No. 299 reproduced below, which shows primarily calcium and magnesium, with weaker lines of silicon, aluminum, nitrogen, and oxygen. Thus, the material that produced this spectrum was severely depleted in iron and sodium; it may have been similar to that of the rare enstatite achondrite meteorites.

These spectra reaffirm that the meteoroidal particles in space are not all similar in composition. This, in turn, may indicate that there have been several sources of such particles.

This unusual spectrum, No. 299, is most notable for the absence of iron or sodium lines. It was produced on August 29, 1970, by a very-high-velocity object in retrograde orbit. The strongest feature is the multiplet of neutral magnesium at about 3830 angstroms. Note the H and K lines of singly ionized calcium at 3968 and 3933 angstroms, respectively. Also present are lines of silicon, aluminum, atomic oxygen, and atomic nitrogen.

WHY IS THE MOON SO DARK?

The moon reflects only about seven percent of the sunlight falling on it, and its surface is actually a dark gray. (The silvery white appearance of the moon to the naked eye is due merely to the lack of a suitable comparison object.)

This darkness has been puzzling, for the moon is covered with a fine rock powder, yet almost all rocks, lunar ones included, become very light when pulverized.

As early as 1955, Thomas Gold (then at Harvard Observatory) suggested that each dust grain might be coated with a very thin, very dark layer, only a few atoms deep. This hypothesis was corroborated in 1964 by Bruce Hapke of Cornell University, who demonstrated how fine rock powders exposed to a laboratory simulation of the solar wind became as dark as the lunar surface.

Now, at the Cornell Lunar Laboratory, E. Bilson and R. L. Baron have used a technique called Auger spectroscopy to analyze the outermost layers of individual lunar dust particles. They find that the surface of each grain is about three times richer in iron than its interior. If this tiny amount of excess iron were not present, moonlight would be about four times brighter than it is.

In reporting this investigation by his coworkers to the fifth annual Houston Lunar Conference, Dr. Gold noted that the greater the iron enrichment in various samples, the darker the material. While many other selenologists believe that lunar areas owe their different shadings to differences in gross chemical composition, he feels that the action of the solar wind in adding traces of material to the surface is a more important factor.

"A longer exposure will result in a darker surface," he said. "The regions that are slightly lighter must be those that have not been exposed quite so long, and these are usually the mountains. The flat plains, which usually are darker, must be the areas of longest exposure."