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Survey of Observations of Meteor Trails

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The general nature of the luminosity and ionization appearing along the trajectories of bright meteors is discussed on the basis of observations made with optical cameras and radar equipment. Six distinct categories of phenomena are described: 1) a sharp luminosity peak that moves with the meteoroid and consists chiefly of the low excitation radiation of atoms in the neutral and first ionization stages, 2) a moving-ball type of radar target that also travels at the velocity of the meteoroid and appears along the highest portion of the trajectory, 3) a trailing wake with duration measured in small fractions of a second and with a faint luminosity arising from the lowest excitation levels in a number of common atoms, 4) a metastable train lasting a second or two along the upper part of the trajectory, the luminosity arising from a forbidden green line of neutral oxygen, 5) a persistent train that may remain visible for several minutes and that probably includes the lines of neutral sodium and magnesium in its luminosity, and 6) an enduring radar echo that lasts for a considerably longer period than the optical persistent train and that, like it, is modified continually by the wind structure of the upper atmosphere.

Introduction

A METEOR[24] is defined as the light phenomenon that results from the entry into the earth's atmosphere of a solid particle from space. The *path* of a meteor is its line of motion as seen on the celestial sphere by the observer, and the *trajectory* is this path when considered in three dimensions with the earth as a reference system of coordinates. The *train* is anything left along the trajectory after the head of the meteor has passed, and the word *wake* is used in referring to train phenomena of very short duration. In this paper, the author is going to use the term *meteor trail* to emphasize the dynamics of the event and the inter-relations between the meteor head and what follows it.

Almost all the instrumental meteor data now available have been secured by use of either photographic or radar techniques. In the former case, very fast cameras covering a wide field are the most efficient.[22] In general, the camera is fixed while both stars and meteor move across the field during an exposure that may last anywhere from 5 min to 1 hr. Where an analysis of meteor luminosity is desired, a prism or transmission grating is placed in front of the lens. The latter is usually more efficient, especially in the case of the larger lenses.[4] A rotating shutter inserted at some point in the optical path adds greatly to the value of any meteor photographs secured.[28] In the case of radar equipment, both directional and omnidirectional antenna systems have been employed.[7, 16] In general, work at the lower frequencies (between 25 and 75 Mc/sec) has been the most successful in collecting meteor records. It is of interest to note that the foregoing techniques, found successful in meteor research, now are being applied to the study of the re-entry of satellites and missiles[35, 3, 13] and to the observation of artificial air glows in the upper atmosphere.[23, 36]

Meteor Heights, Velocities, and Masses

Meteors enter the earth's atmosphere at speeds ranging from just over 10 km/sec (33,000 fps) up to nearly 75 km/sec (250,000 fps). The faster meteors first become visible at heights of 120 to 105 km (400,000 to 350,000 ft) and disappear between 105 and 75 km (350,000 and 250,000 ft). The slow meteors are 20 to 30 km (70,000 to 100,000 ft) lower. A typical average meteor as bright as Vega, Capella, or Arcturus, that is of zero magnitude, moving at 40 km/sec (130,000 fps) appears at a height of 105 km (340,000 ft), reaches maximum light at 93 km (305,000 ft), and disappears at 88 km (290,000 ft). A fireball moving at the same speed but 10^4 times as bright (magnitude -10) appears probably a shade higher in the atmosphere than the fainter object, reaches maximum light at 75 km (250,000 ft), and disappears at 65 km (210,000 ft). The heights and velocities just given are averages from photographic data secured by the Harvard College Observatory.[21]

Thus, in general, meteoric phenomena occur in an environment where the densities and pressures are from 10^{-8} to 10^{-4} the sea level values, temperatures range from 150° to over 400°K, and the molecular mean free path in the undisturbed atmosphere is somewhat between 1 mm and several meters. The range of brightness mentioned earlier, magni-

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tude 0 to −10, corresponds to light emission from 10^3 to 10^7 w. The original diameter of the *meteoroid*, the solid particle itself, is estimated as between 1 and 50 cm, but no good quantitative values are available at the present time, and there is no knowledge of the original shape. There is considerable uncertainty concerning meteoroid masses. As a starting point for discussion, a mass of $\frac{1}{2}$ g can be assumed for a 0 magnitude meteor moving 40 km/sec, and a mass of 5 kg for the −10 magnitude fireball. These figures correspond to a conversion into visible light of about 10^{-3} of the kinetic energy. The range of uncertainty in this value is about two orders of magnitude.

Origin of Meteoroids

It now generally is agreed that the meteoroids that enter the atmosphere and produce meteors have two chief sources of origin, both within the solar system. The great majority are moving in elongated orbits similar to, or identical with, comet orbits.[33, 11] This must be cometary debris. From indirect evidence, it is suggested that these meteoroids have a mean density considerably less than water and a fragile, possibly porous structure that fragments near a dynamic pressure (ρv^2) of roughly 0.02 atm.[32, 30] As a result, no known example of this type of meteoroid has reached the ground as a fragment of any appreciable size. The second type produces an occasional brilliant fireball and is moving in a more nearly circular orbit similar to that of an asteroid.[34] This is asteroidal debris. Such meteroids are stony or metallic in structure with densities from three to eight times that of water. They may survive their passage through the atmosphere and fall to the earth as *meteorites*. In dealing with the physics and dynamics of meteors, it is essential to recognize the two types of meteoric particles.

Meteor Spectra

As noted previously, roughly 10^{-3} of the original kinetic energy of the meteoroid is converted to visible light during its passage through the atmosphere, and, as a very general approximation, about the same amount of energy appears as ionization. Most of the remainder of the energy is converted into heat. Observational evidence indicates that the meteoroid loses kinetic energy by a continuous ablation of mass rather than by any appreciable decrease in velocity.[9] Deceleration becomes significant only in the case of very slow fireballs that penetrate to abnormally low heights. A simplified physical picture of a bright meteor assumes the direct collision between the meteoroid and the air molecules, with the resulting ablation of the solid mass. Through subsequent collisions between the air and the moving cloud of meteor plus air particles, atoms and molecules are excited into energy levels from which radiation is emitted. This results in the characteristic atomic line spectrum of bright meteors along with a few molecular bands, in particular those of nitrogen.[26] The following neutral atoms have been identified reliably in the light of meteors: hydrogen, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, calcium, chromium, manganese, iron, and nickel. The first-stage ionization of the following atoms also appears: nitrogen, oxygen, magnesium, silicon, calcium, iron, and strontium. In general, the excitation is low, most of the multiplets identified having excitations of the upper level between 2 and 8 ev.

Velocity in the atmosphere is the parameter that has by far the greatest effect on the general character of a bright meteor spectrum. The fast meteors have spectra that contain strong lines of a number of singly ionized elements, calcium, magnesium, and silicon being particularly prominent here. Meteors of medium speed have a few ionized lines, but they are not outstanding. The light of slow meteors is from neutral atoms and molecules only. The slowest objects may penetrate the atmosphere to heights where a gas cap builds up in front of the ablating meteoroid.[31] Significant blackbody temperature radiation may be present, but the major part of the light still comes from individual atoms and molecules.[2, 27]

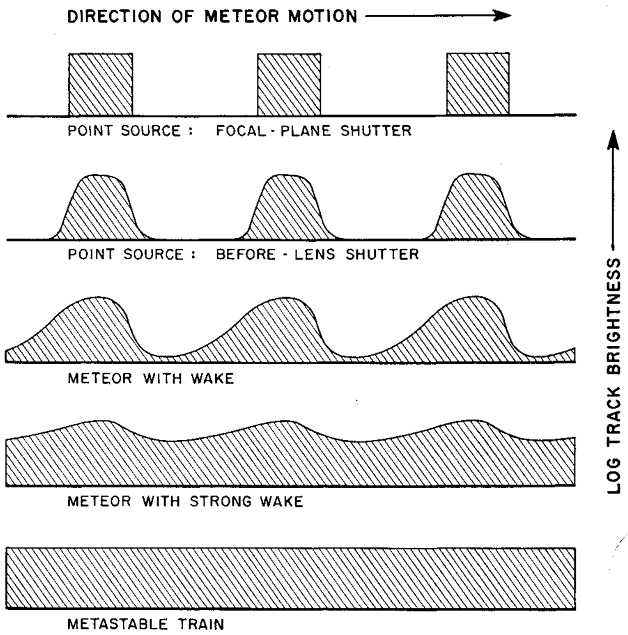

Fig. 1 Effect of the form of the meteor image on meteor tracks photographed using a rotating shutter. In this qualitative illustration, the meteor image is assumed to be of constant intensity and to be moving at a uniform angular velocity from left to right. The closed period for the lens is twice the open period. In actual practice, photographic diffusion effects may modify the record still further.

Meteor Wakes

Of particular interest here is the actual shape and form of the meteor as it moves down its trajectory. The visible object is not the meteoroid itself but the glowing cloud of atoms and molecules which surrounds it. The angular motion across the sky is so rapid that in most cases the persistence of vision will mask the true form of the meteor head, even if it is large enough to be resolved by the eye. Analysis by ordinary photography also suffers on account of the rapid angular motion and various effects of photographic diffusion common with bright images. A very useful device for studying the nature of the moving meteor image is an occulting shutter installed on the camera either in front of the lens or immediately in front of the emulsion. Figure 1 illustrates qualitatively the nature of typical meteor tracks as photographed with a rotating shutter. As one moves farther away from an ideal moving point source, the effects of the shutter occulations become progressively less evident.

Figure 2 is an example of direct meteor photography with a rotating shutter before the lens. It will be seen at once that here much the greatest percentage of the light emitted was concentrated in a relatively small image, but that some trailing luminosity was detected. In an early study of such photographs,[28] it was noted that in most cases of bright meteors there was evidence of a wake extending from 20 to 200 m behind the meteor head, and that in general the integrated luminosity of the wake was considerably less than $\frac{1}{10}$ the luminosity of the head. More recently McCrosky[14] has studied a much larger amount of data on faint meteors photographed with the Super-Schmidt cameras,[22] and he finds that a wake is detected more frequently in the low-velocity objects. He concludes that it is produced by fragmentation of the meteoroid into particles approximately 10^{-5} g in weight. It is probable that the wake found in the case

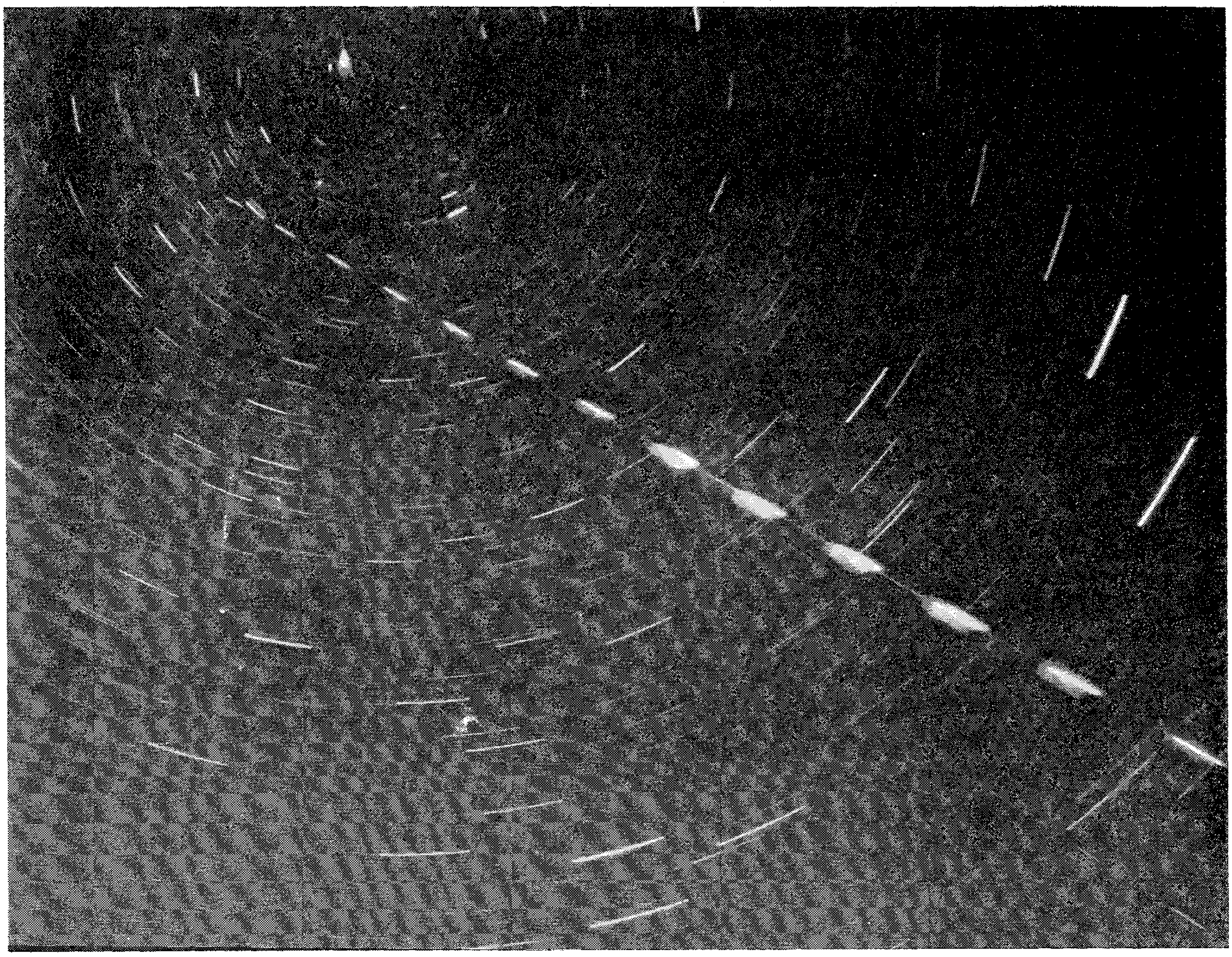

Fig. 2 Photograph of two meteors, secured in Ottawa with a stationary camera and a shutter rotating in front of the lens on August 12–13, 1949. The meteors, with direction of motion from upper left to lower right, had velocities of 60 km/sec (200,000 fps) in the atmosphere. Shutter breaks were at 0.1-sec intervals, the closed period being equal to the open period. Evidence of a wake and the beginning of a persistent train appears in several of the shutter breaks for the brighter meteor, which was of visual magnitude −4 with a train seen in moonlight for 11 sec and an enduring radar echo lasting 112 sec. The short arcs of circles were produced by the stars trailing about the north celestial pole during the 25-min exposure. (Dominion Observatory photograph)

of very bright fast meteors consists essentially of trailing atoms and molecules, whereas the wake for the fainter and slower meteors involves both fragmented particles and the atoms and molecules that are the end product of much of the meteoroid mass.

Figure 3 illustrates the spectrum of a typical wake of the first type. The excitation is very low, the intercombination lines of magnesium and calcium and the lowest-level iron multiplets appearing with unusual strength. The upper energy levels of the brighter multiplets identified range from 2.5 to 3.1 v. This low excitation is typical of much lower velocities than the 60 km/sec (200,000 fps) at which this meteor was moving. Apparently the particles in the wake have been decelerated strongly.

Metastable Trains

In Fig. 4 is shown a different phenomenon, a radiation in the green region of the spectrum (5577A) which has a duration of the order of 1 or 2 sec and hence exhibits no evidence of shutter breaks. Since this is produced by a transition from a metastable energy level of the neutral oxygen atom, the term *metastable train* is suggested as applicable. It first was identified by Halliday[5] and is found in the spectra of the high-velocity meteors, appearing in general along the upper portion of the trajectory. The metastable train occurs normally in the height range 115 to 95 km (370,000 to 300,000 ft), whereas the remainder of the visual luminosity is roughly 10 km lower. The oxygen green-line radiation generally is present in all auroral displays. Its presence in meteor spectra has not yet been explained fully on theoretical grounds.

Persistent Trains

A luminosity of still longer duration frequently is observed in the case of bright meteors, and this has been termed the *persistent train* (Fig. 5). In extreme cases it may last for appreciable fractions of an hour, although maximum durations of a few minutes are more usual. It is correlated with meteor brightness and velocity, being more prominent as these parameters assume higher values.[18] Visual observations and direct photographs of persistent trains show a rapid diffusion and a distortion into various twisted forms by the wind shears present in the upper atmosphere.[21] Liller and Whipple have made a quantitative study of these motions in the case of a few photographic records.[12] Hawkins and Howard[6] find an exponential decay law for the luminosity of a persistent train, with a minimum decay constant in a height range 88 to 96 km (290,000 to 310,000 ft). Unfortunately, no photograph of the spectrum of a persistent train yet has been secured, and so there is some doubt as to the nature of this long-enduring luminosity. Observations made in the nine-

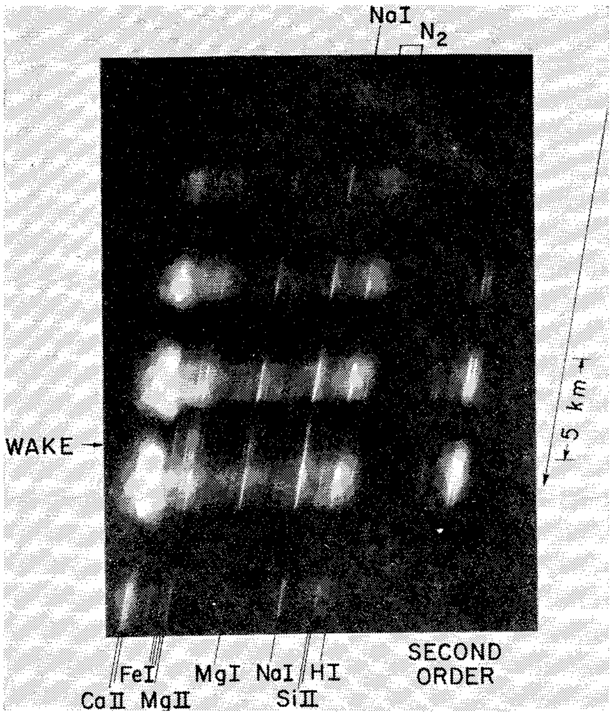

Fig. 3 Meteor spectrum (World List no. 125) photographed in August 1952 with a diffraction grating and a rotating shutter occulting the lens 12 times/sec. The closed period of the shutter was twice the length of the open period. The meteor was moving at 60 km/sec (200,000 fps), so that the shutter interval represents 5 km along the meteor trajectory. The meteor was observed visually, stellar magnitude −4 with a 30-sec train. The lines of both neutral and once-ionized atoms appear in this spectrum, as well as the bands of the nitrogen molecule. The excitation in the meteor head builds up as the meteor brightens, whereas the spectrum of the wake shows a much lower excitation than that of the head. Note, for example, presence of NaI in wake but complete absence of SiII. (Dominion Observatory photograph)

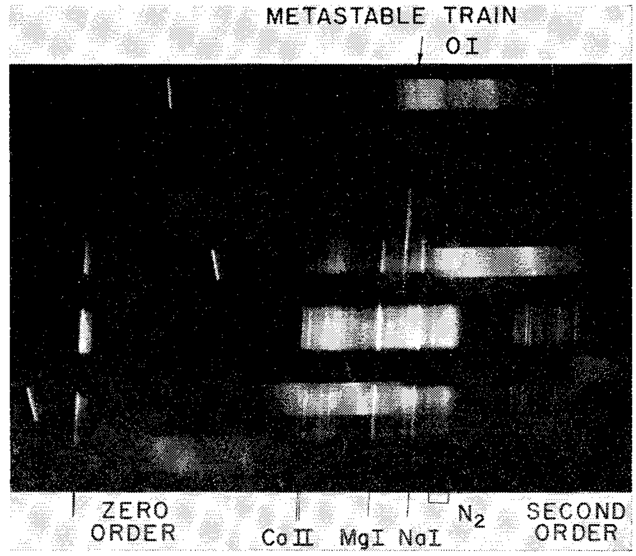

Fig. 4 Meteor spectrum (World List no. 433) photographed in August 1961 with a diffraction grating and a rotating shutter occulting the lens 6 times/sec. The closed period of the shutter was equal in length to the open period. The meteor was moving down, as here presented, at a velocity of 60 km/sec (200,000 fps). It was observed visually, stellar magnitude −2 with a 10-sec train. Apart from some of the strong low-temperature lines of both neutral and once-ionized atoms, the most striking feature is that of the metastable train whose luminosity in the green is produced by the neutral oxygen atom. Since this luminosity lasts for 1 or 2 sec, the train shows no shutter breaks. It starts at a height of 118 km (390,000 ft) and ends at 103 km (340,000 ft), whereas the remainder of the photographic track goes from 109 to 86 km (360,000 to 280,000 ft). In addition to the meteor spectrum, several strong stellar spectra appear on this exposure. The stellar spectrum at the top contains the Balmer lines of hydrogen in absorption.

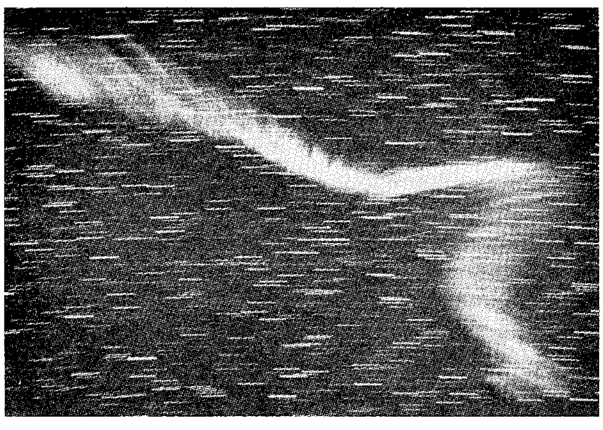

Fig. 5 Persistent train of a bright meteor, April 26, 1956, photographed with a time exposure lasting from 135 to 195 sec after the meteor had appeared. This photograph clearly demonstrates the differential drift of various portions of the train, an effect of upper atmosphere winds. There is also an indication of the break-up of the train into globules, which could be thermal bubbles resulting from the heating of the air column by the meteor. (Photo by C. F. Capen Jr.; courtesy of *Sky and Telescope Magazine*)

teenth century with visual spectroscopes suggest that the yellow line of sodium and a line close to the green line of magnesium are present in the persistent train.[17] Since the same observers correctly identified these two features in the meteor head, it is quite possible that sodium and magnesium contribute to the train luminosity. The spectrum of the brighter meteor in Fig. 2 (not reproduced here) shows a feature very close to the violet line of magnesium as the strongest contributor to the train spectrum,[19] and this does not have the characteristics of the wake as it appears to be of longer duration.

The relations among the various forms of luminosity left along the meteor trajectory are illustrated qualitatively in Fig. 6. Immediately following the passage of the meteor head the position of an intensity maximum will be influenced chiefly by the position of a burst of light in the meteor head. This is presumably a position where the meteoroid fragmented or ablated at an accelerated rate.[8] Later on the position of maximum of the metastable train will be governed by the physical conditions in the upper atmosphere which are favorable to its appearance. Finally, the persistent train will be at maximum strength somewhere near the height where the decay constant is a minimum.[12, 6] In the case of faint slow meteors, fragmentation is the primary factor in determining the form of the light curve.[10, 14] The luminosity may decay rapidly over the upper portion of the trajectory, but the wake of fragmented particles will extend long enough to fill in the shutter breaks on rotating shutter photographs completely. This produces the effect called *terminal blending*, as noted by McCrosky in his study of wakes.[14]

Meteor Radar Echoes

The observational evidence resulting from a radio study of meteors now is examined. High-power radar records of bright meteors show enduring echoes that last considerably longer than the visual trains for the corresponding objects (Fig. 7).[18, 29] These echoes are produced by the clouds of

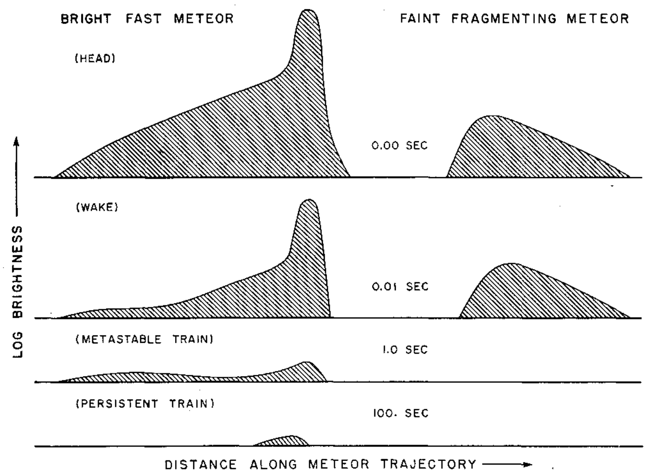

Fig. 6 Qualitative plots of the luminosity along the meteor trajectory. Each plot represents the luminosity as measured at a fixed time in relation to the instant when the meteor head passes the corresponding point on the trajectory. The first plot (0.0 sec) represents the light curve of the meteor, that is, the variation with position of the brightness of the meteor head itself. The following plots (0.01 to 100 sec) represent the luminosity that lags behind the head, measured at the indicated time intervals after the head has passed.

electrons remaining after the ionization of atoms and molecules along the meteor trajectory. As in the case of the visual persistent trains, their forms are modified significantly by the shear pattern of upper atmosphere winds. For example, a very common characteristic found in long-duration meteor radar echoes is a reduction with time to one or more discrete echoing ranges, as if the trail were broken up into a series of knots or nodules.[16, 25] A characteristic pattern in these features sometimes shows a tendency to repeat itself in different bright meteors appearing during the same hour or two. Most of the enduring meteor echoes occur in the height range 80 to 115 km (260,000 to 380,000 ft) with a peak frequency near 98 km (320,000 ft).[20, 25]

A completely different type of echo is the radar head echo, first noted by Hey and Stewart[7] in their observations of the Giacobinid meteor shower in October 1946. The head echo is more frequent for meteors of high velocity, and its observation is facilitated by the use of radar equipment of very high power. In the case of members of the Perseid shower moving at 60 km/sec (200,000 fps), one third of the meteors visually observed have this form of echo when radar at a frequency of 32 Mc/sec is operated at a peak power near 4 Mw.[25] The head echo is a moving-ball type of target which travels with the velocity of the meteor head. It is observed for meteors moving at all angles to the line of sight, including those objects going away from the observer. On the average, it first appears some 10 km higher than the beginning of the visual or photographic trajectory, and generally it disappears above the position of maximum luminosity.[20] Figure 7 reproduces two examples of the head echo. A complete physical explanation is not yet available. One must find a mechanism that almost instantaneously produces a radar target large enough to reflect radio waves 10 m long. It is possible that ionization created by ultraviolet light from the head plays a significant role in the phenomenon, a suggestion first made by McKinley and Millman.[16] A detailed discussion of the amplitude characteristics of the head echo has been published by McIntosh.[15]

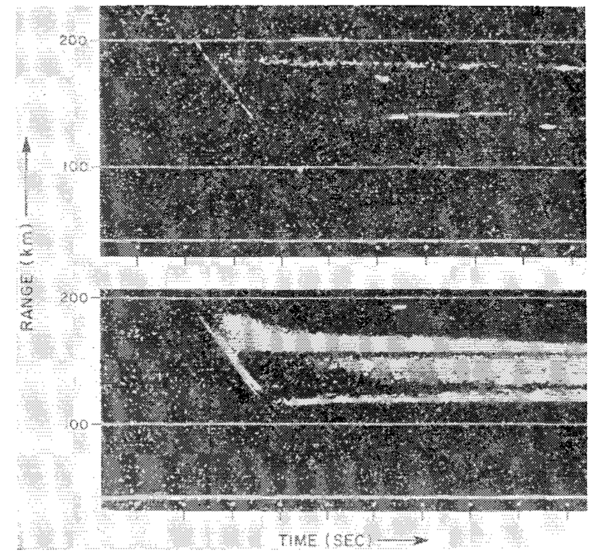

Fig. 7 Two typical examples of meteor echoes showing the head echoes, narrow diagonal lines at left, and the early parts of the enduring echoes. These records were secured in August 1961 with the high-power meteor radar of the National Research Council, operated at the Springhill Meteor Observatory near Ottawa. The upper echo corresponds to a meteor visually observed as of magnitude −1.5 with a 10-sec visual train. The enduring portion of the radar echo lasted for over 2 min. The meteor was moving at 60 km/sec (200,000 fps) while the visible and radar trajectory covered a height range from 115 to 85 km (380,000 to 280,000 ft). The second example occurred when no visual observations were being made. The enduring echo in this case lasted for just under 2 min.

Summary

To summarize, one finds, moving along with a meteoroid in the atmosphere, a high peak of luminosity produced chiefly by atomic line emission, and a moving-ball type of radar target. Trailing behind the ablating and/or fragmenting meteoroid may be a wake of lower-level atomic emissions, a metastable train of neutral oxygen luminosity, a persistent train of long duration radiations, and an ionized cloud of particles that act as an enduring radar target. Some of the possible connections between such observational data and the aerodynamical problems of the future have been outlined in a recent paper by Allen.[1] There now is being accumulated a reasonable body of quantitative information in the field of meteoric astronomy, but our knowledge concerning the spatial distribution of luminosity and ionization in the immediate neighborhood of the meteoroid is still largely qualitative. It is hoped that the current activity in the laboratory study of hypersonic velocities will provide solutions to some of the current problems and will compliment the information gathered by the astronomers.

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