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# METEOR TRAINS

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# Meteor Trains[1]

*By* ROBERT F. HUGHES[2]

The interaction of meteoroids with the earth's atmosphere produces in some instances a luminescence called a meteor train along a portion of the meteor's visible trail. This light may last from seconds to hours, and is much less intense than the luminosity localized about the ablating meteoroid, which is generally the only interaction phenomenon observed. Molecular and atmospheric air motions cause perceptible expansion, distortion, and displacement of the meteor train. Photographic observations of such diffuse and faint sources have been successful only within the last 10 years, and we have not yet obtained a good spectrogram of a meteor train which is imperative for understanding the mechanism responsible for this luminescence.

Visual observations by Trowbridge (1907) of exceptionally long-enduring trains produced by bright meteors indicated that meteor trains form at altitudes from 72 to 104 km, a localized part of the region from 64 to 130 km where meteor trails are observed. The longest-enduring trains were even more sharply localized and occurred at altitudes from 80 to 96 km. The most probable height of train appearance was found to be 88 km, with the frequency falling off rapidly at lower altitudes. The trains observed by Trowbridge had an average duration of about 15 minutes and they frequently underwent large displacements and distortions, attributed correctly to atmospheric air motions in the meteor region. The visual data of Olivier (1947, 1957) indicate the complexity of the winds in the meteor height region. The study of these atmospheric winds has also been a part of the meteor train program at the Harvard College Observatory. This paper presents data on the heights, trajectories, and orbits of 48 train-producing meteors and on the heights, durations, and intensity distributions of the trains.

## Instrumentation and reduction methods

Visual observations have indicated that the distribution of spectral intensity in trains is different from that in meteors, which are normally blue. Trowbridge (1907) found that trains appear as yellow or green with a few strong lines suggestive of the sodium D lines and the 5182A line of MgI. Whipple's (1954) visual observations with a transmission grating indicated a strong continuum in the yellow and red regions with a single reddish line. For photographing meteor trains, therefore, the ordinary blue-sensitive films were replaced by Eastman Super-Panchro-Press and a DuPont Company Panchromatic Film No. 428. The Super-Schmidt meteor cameras (Liller and Whipple, 1954) used to obtain photographic data on meteors and meteor trains were operated from the New Mexico station, whose geographic positions are listed in table 1.

Data on eight of the meteors and their associated trains were reduced by an exact method developed by Whipple and Jacchia (1957) and Cook and Hughes (1957). A rapid graphical method of meteor trail reduction developed by McCrosky (1957) was used to obtain trajectories and heights for the remaining 40 trains. This method allowed a complete trajectory analysis in about 30 minutes with mean errors in velocity and height around 5 percent.

The absolute visual magnitude at maximum luminosity was measured by the photometric process described in detail by Whipple and Jacchia (1957). A constant meteor color index

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[2] Now with General Electric Company, Philadelphia, Pa.

TABLE 1.—*Positions of meteor cameras*

| Position | Camera stations | | | |
|---|---|---|---|---|
| | (1952–1954) | | (1954–1958) | |
| | Las Cruces | Doña Ana | Mayhill | Sac Peak |
| Longitude west | 106°36′42. 3″ | 106°47′58. 4″ | 105°28′17. 5″ | 105°49′13″ |
| Latitude north | 32°18′13. 6″ | 32°30′21. 7″ | 32°54′44. 3″ | 32°47′16″ |
| Height above sea level (ft.) | 5, 141 | 4, 632 | 6, 570 | 9, 253 |

of −1.9 was assumed. The zenithal correction to the magnitude was neglected because the trains were near the zenith, and the average correction would have amounted to only 0.04 magnitude. Errors due to variations in film sensitivity, development, and light transmission are estimated by Jacchia to be about ±0.3 mag. With a single exception, magnitude measurements made from the two stations agreed within these limits. Except for possible errors in the color index, individual absolute visual magnitudes are considered to be accurate within ±0.4 mag.

Orbital elements of train meteors were computed to investigate the type of meteoroids that produced trains; however, observational errors preclude the computation of precise individual orbits, especially for high velocity meteors. The method of orbital computations detailed by Porter (1952) was programmed on an electronic computing machine for the 40 trajectories obtained by the rapid graphical method of reduction. Deceleration due to atmospheric resistance was neglected. Corrections in velocity and radiant to allow for the earth's attraction are significant only for low velocities and radiants of large zenith angle, when the true and apparent values of velocity and zenith can differ by about 4 km/sec and 5° respectively. Although the zenithal corrections are comparable to the trajectory errors, they were included in the orbital calculations. The angular orbital elements, such as inclination, are probably more accurate than the linear elements involving the semimajor axis.

The heights of meteor trains were determined by simply matching the fields of the train and meteor films and noting the dash numbers. This process was possible because train and meteor cameras were at the same location. The maximum and minimum heights, which were measured on all train films, usually occurred in the first exposure. The light intensity of most trains followed a distribution pattern similar to that of meteors. The intensity increased from the beginning height to a maximum beyond the midpoint of the train, then decreased more rapidly to the endpoint. The heights of maximum intensity were measured.

For 12 of the trains the luminosity was interrupted by a relatively faint region generally about five meteor dashes in length, which corresponded to 5 to 10 millimeters on the film. These trains showed effectively two intensity maxima, although no such variation appeared in the meteor trails. The double maxima could be observed even in the first train image, which corresponds to a train-life of about one or two seconds. Because this time is so short, these variations in brightness are considered to be intrinsic phenomena and not the result of the influence of air motions on the train.

If the multiple variations were caused by atmospheric winds, one might expect that points of minimum train intensity would correspond to heights of maximum wind speeds, and that points of maximum intensity would coincide with levels of zero wind. If the correlation coefficient of the horizontal wind field becomes zero in the vertical direction in a height interval of about 5 km (Liller and Whipple, 1954), then trails that extend over 25 vertical kilometers should show as many as five intensity maxima. This argument is based on the assumption of a sinusoidal variation of the horizontal wind with altitude. Furthermore, if the variations were caused by atmospheric winds, the distance between intensity maxima should be greater than 10 km. The fact that the average separation of intensity maxima is only 7 km and that triple maxima are not observed suggests that the double maximum in train luminosity is an intrinsic phenomenon. By the third or fourth image, corresponding to a train life of about five seconds, one of the maxima had generally disappeared. During the remaining lifetime of the train, the intensity distribution resembled that of a single maximum train. The luminosity in the region of this second maximum usually remained the most intense region until the train image disappeared entirely. Three trains were observed, however, whose last visible portion did not coincide with either maximum.

No trains exhibiting three or more variations in luminosity were found. For the 12 trains that showed two maxima, the heights and relative brightness of the maxima in the first or second images were recorded. For the three meteor trains in which a "burst" occurred, the burst region never became the longest enduring portion of the train.

Without consideration of meteor velocity, the entire sample of 48 trains was somewhat arbitrarily divided into two groups, those lasting less than and those lasting longer than about 6.5 seconds. For the 13 trains of longer duration, the height at which the last luminescence disappeared was called the "persistent" point. No quantitative measurements were made of the actual brightness of the train images nor of their rate of decay.

To estimate the duration of the train we must consider the operational procedure in detail. Cook and Hughes (1957) determined that a time interval ranging from 0.75 to 1.4 seconds elapsed between the first appearance of the meteor and the opening of the train camera by the visual observer. Most of this delay may be attributed to the reaction time of the observer. In this paper the duration $t$ of the train is arbitrarily measured from the time of maximum meteor luminosity. For the average meteor it is assumed that the time interval between the opening of the train camera and the first appearance of the meteor is 1.5 seconds. The time interval between first appearance and maximum meteor luminosity is about 0.5 seconds. The exposure lengths were 0.5 seconds for the first image and 2 seconds for the remaining images, with a negligible time interval between exposures. The mean values of $t$ for the various images are then 1.25, 2.5, 4.5, 6.5 . . . seconds. The errors are estimated to be of the order of one second.

## Meteor train data

The data obtained for the meteor trains are listed in table 2. The asterisks indicate that the meteor was reduced in detail by Jacchia. All heights were measured above sea level. The quantities given in the table are defined as follows:

Meteor number: The number of the meteor trail as listed in the Harvard Catalogue.

Date: Time of observation in Universal Time.

Class: Name of the shower to which meteor belongs. A blank indicates a sporadic meteor.

Corr. rad.: Apparent radiant corrected for zenith attraction (Equinox 1950).

$V$: Meteor's velocity in the atmosphere (km/sec).

$V_H$: Heliocentric velocity of meteor at time of capture (km/sec).

$a$: Semimajor axis of the orbit (a.u.).

$e$: Eccentricity of the orbit.

$q$: Perihelion distance (a.u.).

$q'$: Aphelion distance. "Hyperbolic" orbits are indicated by $\infty$ (a.u.).

$\omega$: Argument of perihelion measured along the orbit from the node in the direction of motion (Equinox 1950).

$\Omega$: Longitude of the ascending node (Equinox 1950).

$i$: Inclination of the orbital plane to the ecliptic (Equinox 1950).

$\epsilon$: Apparent elongation angle, the angle between the earth's apex and the apparent radiant of the meteor.

$\cos z$: Cosine of the zenith angle.

$M_{vis}$: Absolute visual magnitude of the meteor at maximum luminosity.

Duration: Duration of train (sec.).

$H_{beg}(M)$: Height (km) of the beginning point of meteor.

$H_{max}(M)$: Height (km) of maximum meteor luminosity.

$H_{end}(M)$: Height (km) of the end point of meteor trail.

$H_{beg}(T)$: Height (km) of the beginning point of the train.

$H_{end}(T)$: Height (km) of the end point of the train.

$H_1$: Height (km) of the brightest point of the train in the first exposure.

$H_2$: Height (km) of the fainter maximum in the first to third exposures, in trains showing two intensity maxima.

$H_p$: Height (km) of persistent point of train.

## Train-producing meteors: Magnitude distribution

Among the 48 photographic train meteors described in table 2, only seven were members of meteor showers. The Perseids and Southern Taurids each produced three train meteors, and the Geminids one. The successfully recorded trains produced by sporadic meteors occurred in equal numbers in the periods January to June and July to December. In the latter period the observed trains were concentrated in the winter months of November and December, which is to be expected from the weather conditions in New Mexico. A histogram showing the distribution of magnitudes of train-producing meteors is shown in figure 1.

The faintest meteor that can be photographed with the Super-Schmidt meteor cameras has an absolute visual magnitude about +4. The faintest train-producing meteor detected had a magnitude of +2.5. The difference between these magnitudes is due to the fact that train meteors have a high velocity. The number of train-producing meteors increases with increasing meteor magnitude until we approach the limits of sensitivity. We may infer that formation of meteor trains in the earth's atmosphere is a common phenomenon, although the occurrence of luminescence lasting ten minutes or more is obviously very rare.

## Train-producing meteors: Velocity

The velocities of 48 train meteors are shown by a histogram in figure 2. About 12 percent of the meteors have velocities between 70 km/sec and the parabolic limit, and more than 80 percent have velocities greater than 50 km/sec. No train meteors were observed with velocities less than 20 km/sec. The mode lies between 60 and 70 km/sec and the average is about 60 km/sec. The predominance of high velocities is indicated by comparing figure 2 with a similar histogram in figure 3 (Hawkins and Southworth, 1958). Although 80 percent of the meteors in figure 3 have velocities less than 50 km/sec, only a small percentage of such meteors produce trains.

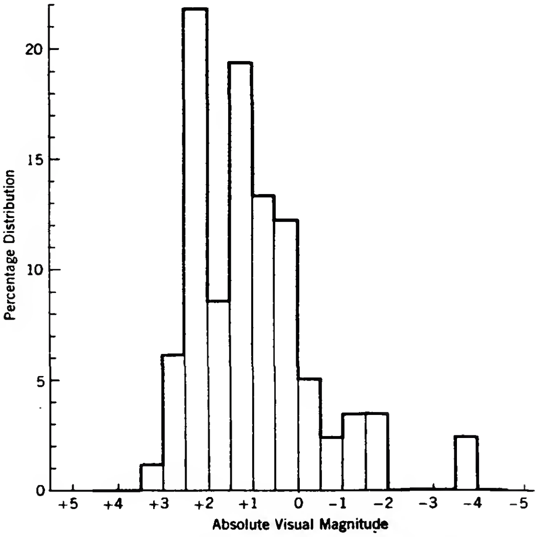

FIGURE 1.—Percentage distribution according to magnitude of 48 train-producing meteors.

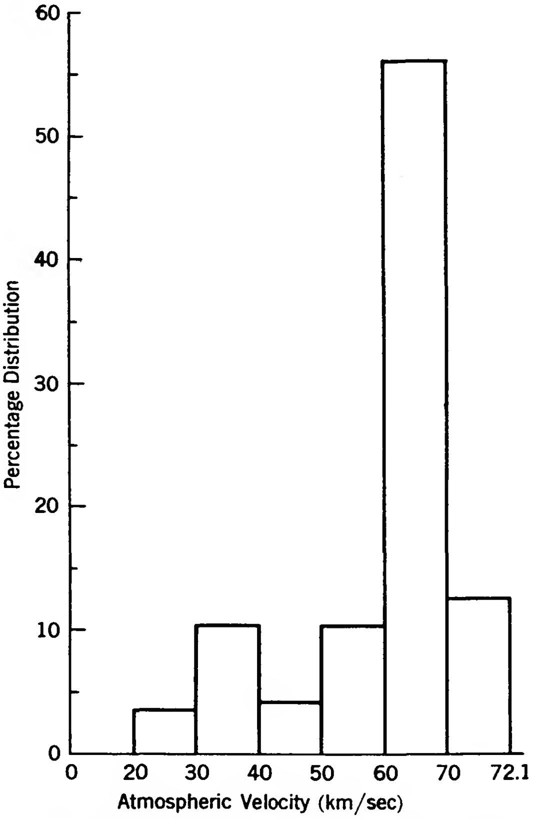

FIGURE 2.—Percentage distribution according to velocity of 48 train-producing meteors.

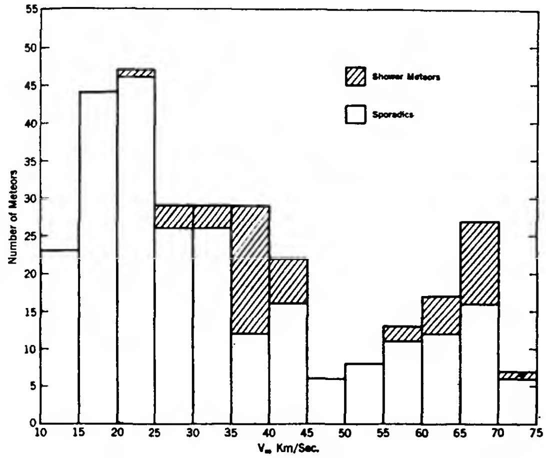

FIGURE 3.—Velocity distribution of 252 sporadic and 49 shower meteors.

## Train heights

Figure 4 shows a plot of the data given in table 2 for the heights of the beginning point, end point, maximum intensity, and persistent points of each train. Figure 4 also shows the mean beginning height and end height of the meteors that produce the trains. A correspondence exists between the beginning heights and end heights of meteor and train, except that at low velocities the beginning height of the train is below that of the meteor. For the trains of very long duration, however, Trowbridge (1907) and Olivier (1957) observed no relationship between the extreme points of the meteor trail and train.

This indicates the restricted height region of train formation. The meteors producing these trains of very long duration were generally ex-

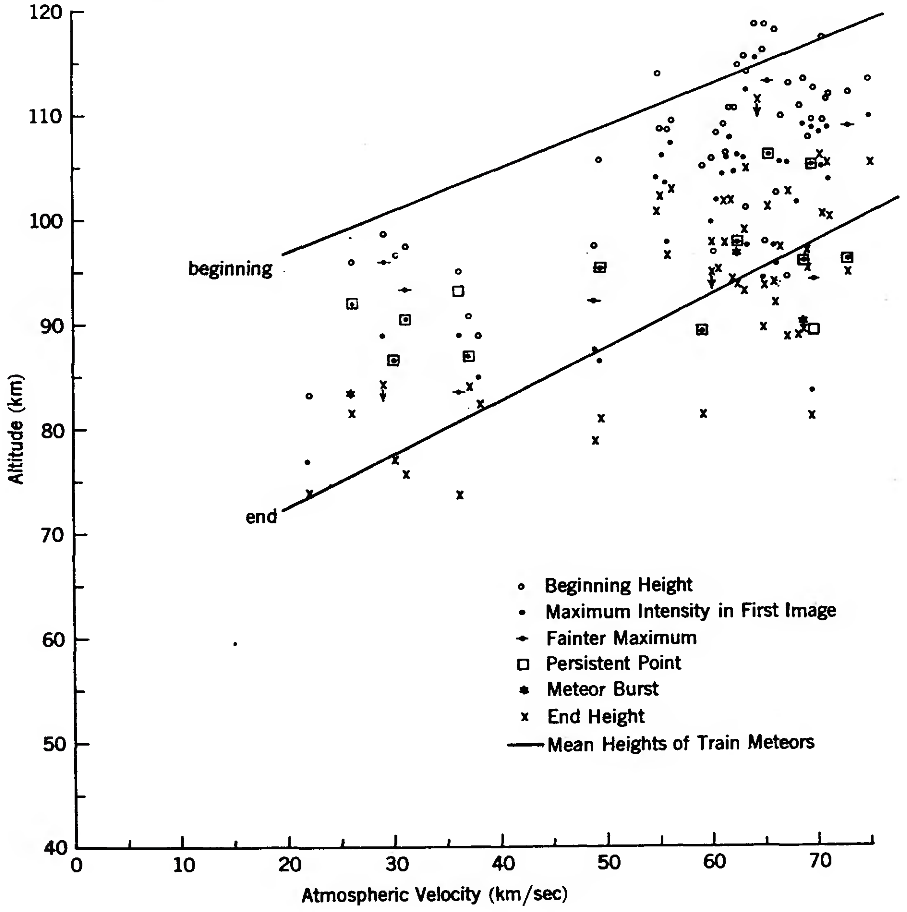

FIGURE 4.—Heights of 48 trains and train-producing meteors.

tremely bright fireballs. They would therefore have trail extremity points outside of the 70–120 km region and no correlation would be expected. The relatively fainter and more numerous meteors observed with the Super-Schmidt cameras have trails that are within the height region of 70–120 km in which the trains are found.

The correlation between the heights of meteor trails and trains is readily seen in figures 5 and 6. For most individual meteors, the trail extremities defined the limits of train formation, although a few trains did fall outside this range. With meteors of lower velocities, the trains with midpoints at heights around 85 km tend to be shorter than the trails. We may write the relation between the beginning heights of trains, $H_{beg}(T)$, and of meteor, $H_{beg}(M)$, as

$$H_{beg}(T)=1.47\ H_{beg}(M)-57\ \text{(km)} \quad (1)$$

and the relation between the end heights as

$$H_{end}(T)=H_{end}(M)+2\ \text{(km)}. \quad (2)$$

The standard deviation for equation (1) is about ±3 km, and for equation (2) it is ±1.5 km. Thus the correlation is slightly better for the end heights than for the beginning heights.

The close relationship between the endpoints of trains and meteors suggested a similar relation between maximum luminosity in trains and

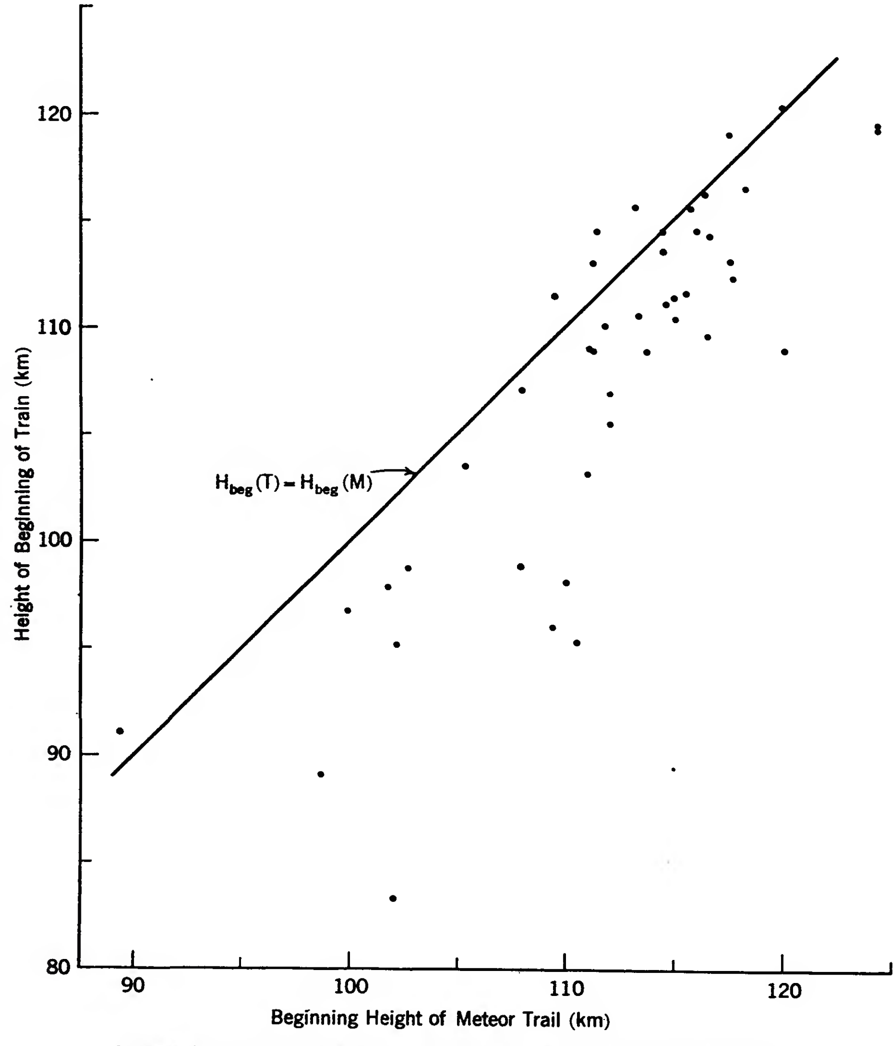

FIGURE 5.—Correlation between beginning heights of meteor trains and trails.

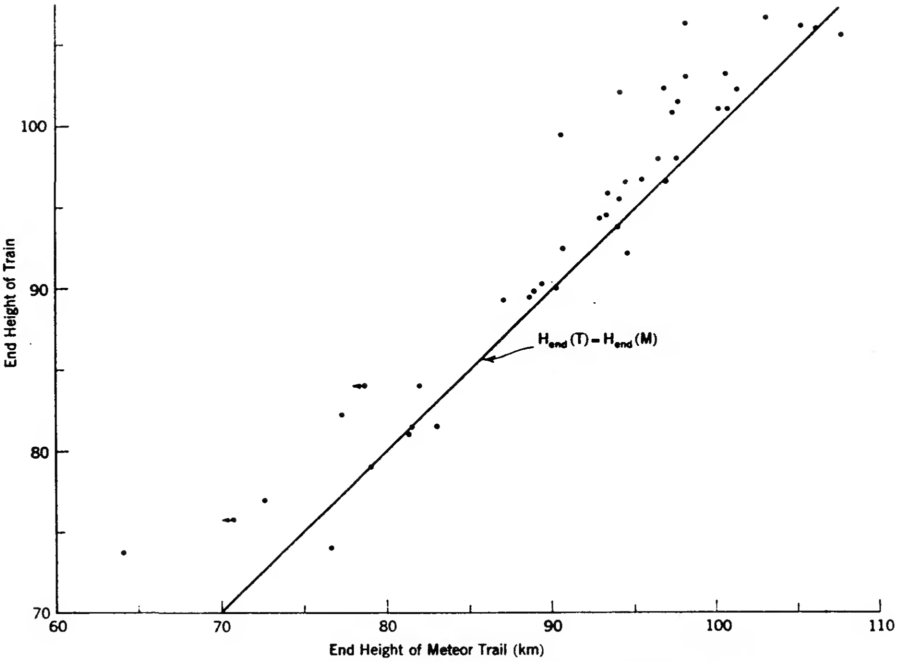

Figure 6.—Correlation between end heights of meteor trains and trails.

in meteors. The relevant data are plotted in figure 7 for 36 trains that showed only a single intensity maximum along the trail. Included among this number are five persistent trains. The graph clearly indicates a coincidence of the heights of maximum intensity for trains and meteors. The agreement appeared to be independent of the exact number of the images, i.e., whether the duration of the train was short or long. This statement must be qualified somewhat, however, because one of the five trains lasting longer than 6.5 seconds departed significantly from this relationship. This train meteor was a member of the Southern Taurid shower, with $H_{max}(M)=78$ km and $H_{max}(T)=87$ km. This apparent exception, however, is actually typical of long duration trains formed by low velocity meteors (see p. 87).

Figure 8 shows a plot of the heights of 12 trains that exhibited double maxima against the height of maximum meteor luminosity; 8 of the 12 trains had durations greater than 6.5 seconds, while only 5 out of 34 trains showing a single maximum had such durations. The average duration of the double maxima trains was longer than that of the single maximum trains. Figure 8 indicates that the lower maximum coincides with $H_{max}(M)$ for altitudes above about 85 km. The lower maximum was brighter than the upper in the first and second exposures for 75 percent of the trains.

### Train durations

Duration of meteor trains varies with meteor magnitude and velocity, as shown in figures 9 and 10. The solid curves in figure 9 represent visual data taken from Millman (1950). Although the scatter is quite large, the curves suggest that the duration of trains increases with meteor magnitude for durations less than 12 seconds. The increase amounts to about 5 seconds per magnitude. The trains formed by low velocity meteors, as a group, deviate the most from Millman's curves. These meteors produce the trains in the constant-height region 85 to 95 km, far above the height of maximum meteor luminosity as shown in figure 8.

Figure 11 shows a plot of meteor magnitude against meteor velocity for the two groups of trains having durations less than and greater than 6.5 seconds. The magnitude-velocity variation for the latter group is normal, since

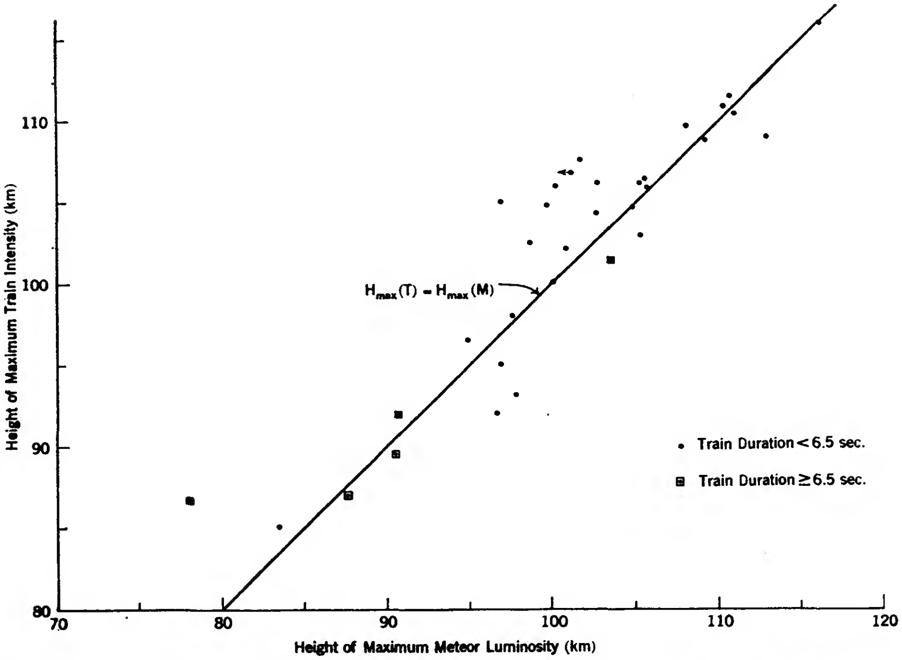

FIGURE 7.—Correlation between heights of maximum luminosity of meteors and trains with single maximum.

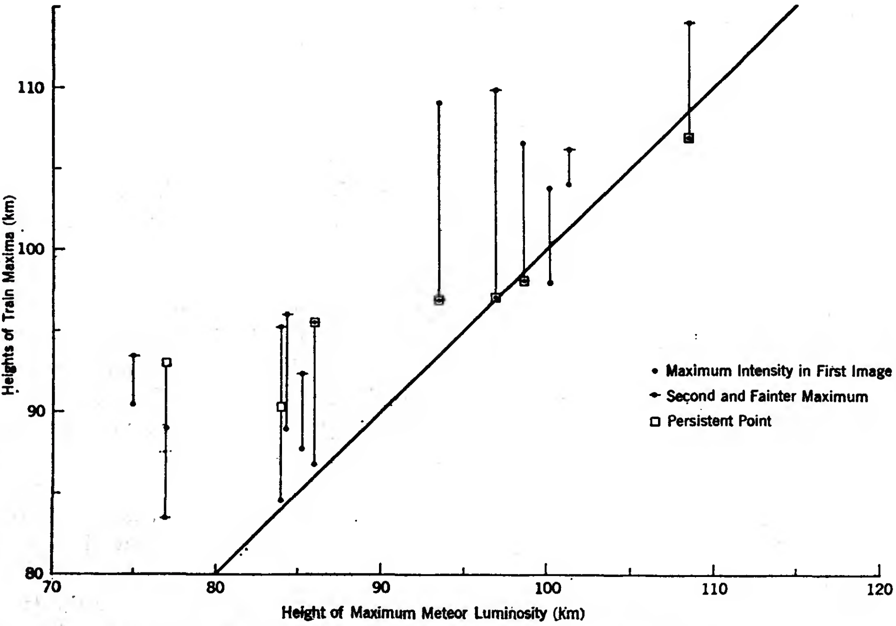

FIGURE 8.—Correlation between heights of maximum luminosity of meteors and trains with two maxima.

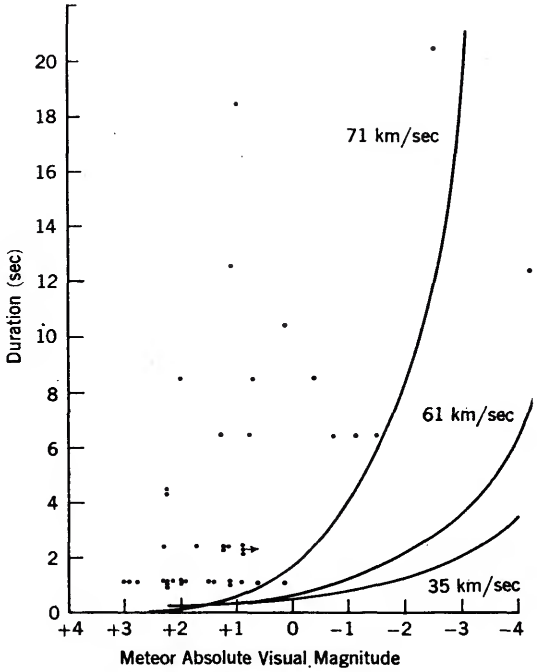

FIGURE 9.—Variation of train duration with magnitude of meteor.

luminous intensity increases with increased mass and velocity of the meteoroid. A difference of about four magnitudes exists between the meteors of low and high velocity, a value consistent with the assumption that the meteoroids in each group have equal masses and zenith angles.

Thus the probability of observing a long-duration train depends to some extent on the energy of the meteor. It must be remembered however that the probability of observing a train may also depend on atmospheric and other conditions that can affect its rate of decay.

The heights of the persistent point for 13 trains with durations greater than 6 seconds are plotted in figure 12. These heights range from 87 to 107 km with an average value of 94 km and a dispersion of 6 km. The relation of the persistent height to $H_{max}(M)$ was seen in the previous sections to be similar to that of the single and double maxima; that is, the persistent points coincide with the heights of maximum meteor luminosity except in the region where $H_{max}(M)$ is less than 85 km. All of the five persistent points at heights above 96 km were formed by high-velocity meteors. The obvious lack of persistent trains in the region below 85 km qualitatively agrees with the values of Liller and Whipple (1954) for the large decay rate of luminescence in this region. A striking example of this phenomenon is the meteor of June 29, 1954, which burst at 83 km; yet the height of the persistent point was 92 km. On the other hand, another meteor which burst at 91 km showed a persistent point at 97 km.

### Orbits of train meteors

The three train-producing meteors of low velocity, with persistent points much greater than $H_{max}(M)$, were shower meteors, one Geminid and two Southern Taurids. Their orbits are characterized by small inclinations, perihelion distances less than 0.4 a.u., and aphelion distances that lie within Jupiter's orbit. The remaining five low-velocity train-meteors listed in table 2 had heights of maxi-

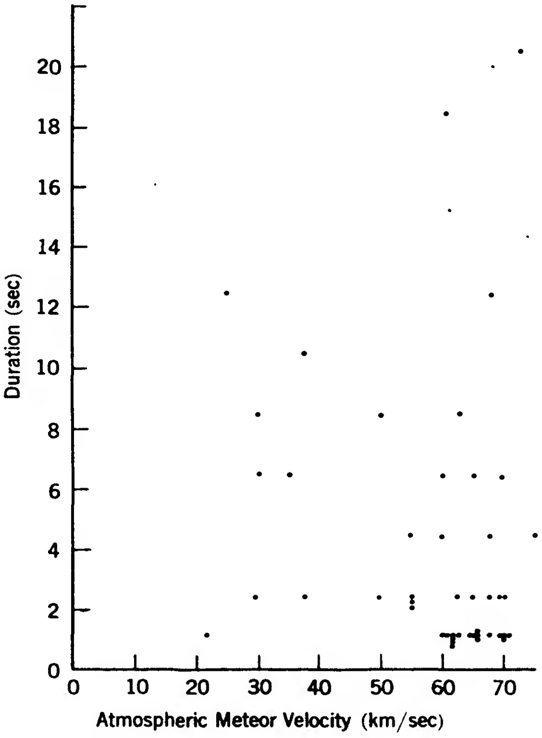

FIGURE 10.—Variation of train duration with velocity of meteor.

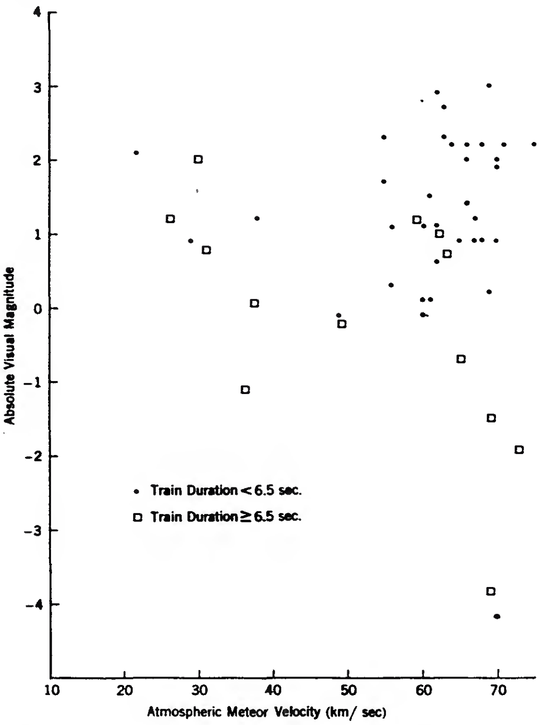

FIGURE 11.—Variation of magnitude with velocity for train meteors.

mum luminosity greater than 85 km which coincided with the height of maximum train luminosity. Two of these train meteors were in orbits identical to those of the three shower meteors; the others had small inclination angles but the perihelion distances were about unity and aphelion distance lay beyond Jupiter's orbit.

In summary, five out of eight low-velocity train meteors possessed orbits of short period, low inclination, and high eccentricity; the other three were similar except that they had longer periods. The average value of the eccentricity of the low-velocity meteors was 0.87. Individual values were all greater than 0.8, which made the value of the cometary-asteroid criterion, $K$ (Whipple 1954), greater than zero for each orbit.

The trains with the five largest $H_{max}(M)$ were formed by high-velocity meteors, one of which was a Perseid. Each of these five train meteors possessed an orbital inclination greater than 120°, aphelion distance greater than 6 a.u., and four of them had perihelion distances near unity. Eccentricities were about unity with one exception, when $e=0.7$, a value that is still

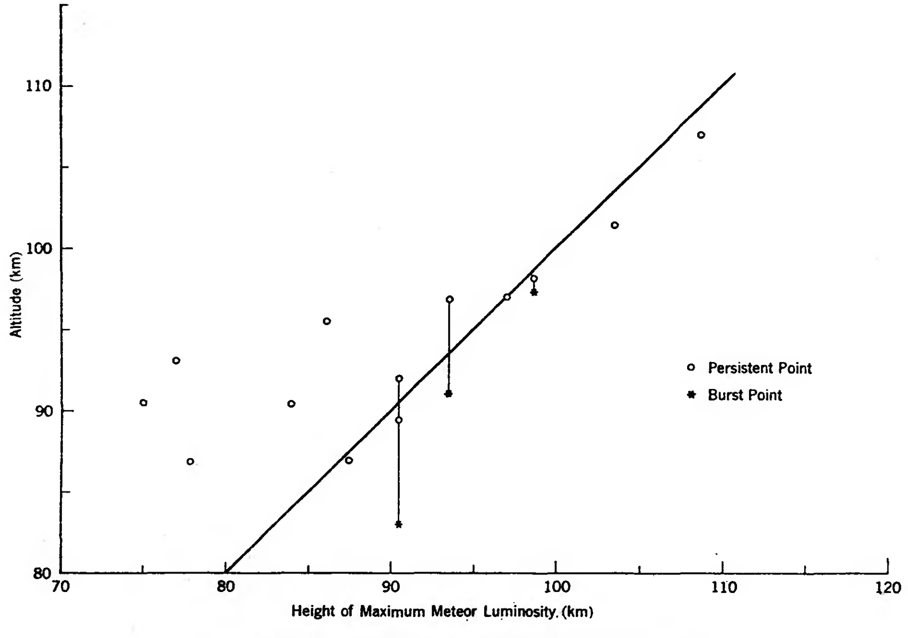

FIGURE 12.—Heights of persistent point of meteor trains.

larger than the asteroidal limit. The comet-asteroid criterion was positive for these meteors also. The meteors that provided the two longest-duration trains were among this group. The five longer-duration trains with $H_{max}(M)$ near 85 km resulted from both high and low velocity meteors.

The trains of short duration were formed by high velocity meteors. With the single exception of the meteor of April 27, 1954, the inclination angles are greater than 90°, aphelion distances are greater than 8 a.u., and the eccentricities are larger than 0.8; these values make the cometary-asteroid constant strongly positive. Orbits with eccentricity values near unity resulted in perihelion distances less than 0.5 a.u. for 25 percent of the 31 train meteors of short duration. The majority had a perihelion distance, $q=1$ a.u., a value consistent with their greater probability of observation.

Figure 13 shows regions of positive and negative values of the cometary-asteroid criterion ($K$) in equation (3).

$$K=\log_{10}\left[\frac{a(1+e)}{1-e}\right]=1. \qquad (3)$$

Of the 48 meteors, only the one of 3 January 1954 appeared in the asteroidal region of negative $K$, but this meteor had a high atmospheric velocity, an apparent elongation angle of only 17°, and an orbital inclination of 150°. Since retrograde orbits are not characteristic of asteroidal orbits, this meteor is also a cometary meteoroid.

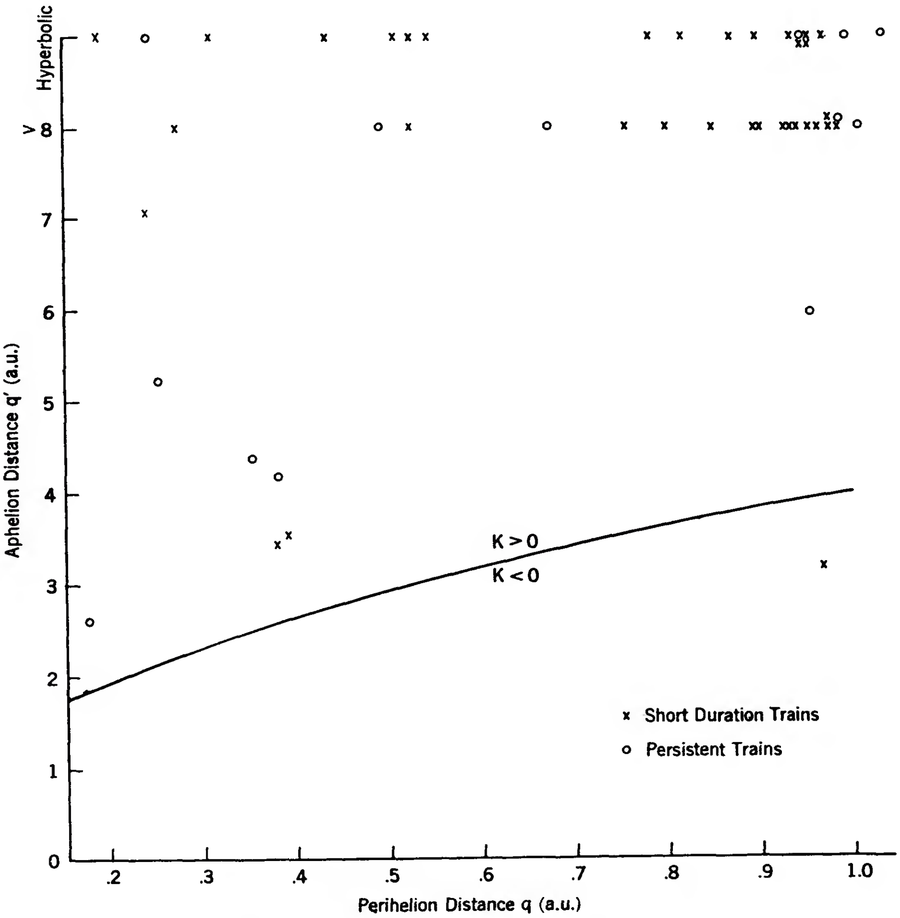

FIGURE 13.—Distribution of aphelion and perihelion distances.

TABLE 2.—*Data on 48 meteor trains*

(* Reduced in detail by Jacchia)

| Meteor No. | 8761 | 8753 | 11660 | 9809 | 10327* | * | 11694 | 11697 | 11701 | 11704 | 10102 | 10130 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 1-1-54 | 1-3-54 | 1-19-55 | 3-7-54 | 3-8-54 | 3-20-53 | 3-28-55 | 3-28-55 | 3-29-55 | 3-30-55 | 4-1-54 | 4-5-54 |
| U.T. | 12:24 | 12:05 | 11:35 | 09:31 | | | 08:25 | 09:22 | 11:04 | 11:10 | 11:30 | 06:10 |
| Class | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. |
| Corr. rad. $\alpha$ | 118°7 | 201°8 | 213°5 | 214°3 | | 265°6 | 175°0 | 264°9 | 274°9 | 315°0 | 269°1 | 229°3 |
| $\delta$ | 22°4 | 8°3 | 24°7 | −4°5 | | −6°2 | 16°3 | 3°0 | −31°0 | −12°8 | 9°3 | 16°1 |
| $V$(km/sec) | 70 | 66 | 62 | 65 | 72.8 | 68.6 | 22 | 55 | 70 | 63 | 65 | 49 |
| $V_H$(km/sec) | 44 | 37 | 41 | 47 | 42.3 | 39.9 | 40 | 36 | 40 | 41 | 43 | 46 |
| $a$(a.u.) | −5.6 | 2.1 | 6.5 | −2.1 | −352.6 | 4.78 | 4.6 | 1.9 | 4.7 | 16 | −12 | −2.9 |
| $e$ | 1.16 | 0.53 | 0.85 | 1.09 | 1.003 | 0.794 | 0.83 | 0.80 | 0.79 | 0.98 | 1.08 | 1.15 |
| $q$(a.u.) | 0.89 | 0.97 | 0.95 | 0.19 | 1.058 | 0.985 | 0.80 | 0.39 | 0.98 | 0.28 | 0.93 | 0.43 |
| $q'$(a.u.) | H | 3.2 | 12 | H | H | 8.57 | 8.41 | 3.5 | 8.4 | 32 | H | H |
| $\omega$ | 214. | 162. | 201 | 304 | 324.4 | 193.1 | 236 | 236 | 15 | 62 | 210 | 274 |
| $\Omega$ | 281 | 283 | 299 | 347 | 261.0 | 359.4 | 7.5 | 7.5 | 189 | 9.6 | 12 | 16 |
| $i$ | 138. | 150. | 118 | 149 | 23.4 | 150.0 | 6.8 | 117 | 167 | 168 | 123 | 65 |
| $\epsilon$ | 27 | 17 | 36 | 43 | 63.1 | 16.7 | 107 | 40 | 8.3 | 35 | 35 | 68 |
| cos$_Z$ | .946 | .836 | .846 | .764 | .611 | .450 | .912 | .764 | .318 | .203 | .880 | .581 |
| $M_{vis}$ | <+0.9 | +2.2 | +2.9 | −0.9 | −1.9 | −3.8 | +2.1 | +2.3 | +1.9 | +2.3 | +0.9 | −0.1 |
| Duration (sec) | 2.5 | 1.2 | 1.2 | 1.2 | 20.5 | 12.5 | 1.2 | 1.2 | 1.2 | 2.5 | 2.5 | 2.5 |
| $H_{beg}(M)$(km) | >113 | 105 | 116 | 108 | 117.5 | 114.4 | 102 | 111 | 113 | 103 | >110 | 102 |
| $H_{max}(M)$(km) | >113 | 95 | 111 | 92 | 96.9 | 84.1 | 80 | 105 | 106 | 98 | 97 | 85 |
| $H_{end}(M)$(km) | 103 | 91 | 102 | <81 | 93.3 | <78.6 | 77 | 101 | 100 | 94 | 90 | 79 |
| $H_{beg}(T)$(km) | 118 | 103 | 112 | 99 | 113.0 | 113.4 | 83 | 109 | 110 | 102 | 117 | 98 |
| $H_{end}(T)$(km) | 107 | 92 | 112 | <89 | 95.8 | 81.9 | 74 | 102 | 101 | 94 | 90 | 79 |
| $H_1$(km) | 109 | 96 | 112 | <89 | 97.1 | 84.6 | 77 | 106 | 106 | 98 | 95 | 88 |
| $H_2$(km) | | | | | 109.8 | 95.2 | | | | | | |
| $H_p$(km) | | | | | 97.1 | 90.4 | | | | | | 92 |

| Meteor No. | 9814 | 10095* | 10128* | 10130 | 10145 | 10138 | 10135 | 10594 | 10597 | 10570 | 10567[1] | 8136 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 4–7–54 | 4–9–54 | 4–27–54 | 4–27–54 | 5–9–54 | 5–9–54 | 5–10–54 | 6–1–54 | 6–1–54 | 6–28–54 | 6–29–54 | 8–3–53 |
| U.T. | 07:23 |  |  | 09:21 | 10:26 | 11:36 | 11:15 | 08:55 | 10:34 | 08:54 | 06:29 | 04:55 |
| Class | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. |
| Corr. rad. $\alpha$ | 270°7 |  |  | 309°3 | 338°2 | 345°6 | 335°9 | 269°5 | 355°1 | 18°7 | 252°4 | 37°5 |
| $\delta$ | 13°7 |  |  | 31°8 | −0°3 | −3°1 | 10°3 | −10°0 | 7°8 | 55°9 | 54°5 | 55°2 |
| $V$(km/sec) | 60 | 49.3 | 37.6 | 56 | 69 | 67 | 68 | 38 | 70 | 69 | 26 | 64 |
| $V_H$(km/sec) | 41 | 42.0 | 37.9 | 43 | 43 | 42 | 44 | 39 | 43 | 56 | 41 | 44 |
| $a$(a.u.) | 8.8 | 167.7 | 2.73 | −14 | −15 | −36 | −5.5 | 3.7 | −11 | −0.6 | 14 | −4.3 |
| $e$ | 0.90 | 0.996 | 0.907 | 1.06 | 1.04 | 1.01 | 1.13 | 0.93 | 1.07 | 2.30 | 0.93 | 1.22 |
| $q$(a.u.) | 0.89 | 0.670 | 0.254 | 0.94 | 0.68 | 0.50 | 0.72 | 0.24 | 0.78 | 0.81 | 1.0 | 0.95 |
| $q'$(a.u.) | 17 | 335 | 5.20 | H | H | H | H | 7.1 | H | H | 28 | H |
| $\omega$ | 219 | 110.5 | 304.9 | 151 | 112 | 90 | 118 | 306 | 124 | 136 | 191 | 153 |
| $\Omega$ | 18 | 20.0 | 37.6 | 37 | 49 | 49 | 50 | 71 | 71 | 97 | 98 | 131 |
| $i$ | 113 | 80.4 | 31.7 | 98 | 164 | 174 | 144 | 25 | 163 | 103 | 34 | 114 |
| $\epsilon$ | 40 | 59.9 | 69.8 | 50 | 23 | 28 | 29 | 72 | 20 | 54 | 101 | 40 |
| $\cos z$ | .355 | .669 | .700 | .546 | .357 | .610 | .580 | .750 | .524 | .510 | .925 | .170 |
| $M_{vis}$ | +0.1 | −0.2 | +0.1 | +1.1 | +3.0 | +1.2 | +2.2 | +1.2 | +2.0 | +0.2 | +1.2 | +2.2 |
| Duration (sec) | 4.5 | 8.5 | 10.5 | 2.5 | 1.2 | 2.5 | 4.5 | 2.5 | 1.2 | 2.5 | 12.5 | 1.2 |
| $H_{beg}(M)$(km) | >104 | 112.0 | 89.3 | >106 | 120 | 116 | 111 | 99 | 118 | 115 | 109 | 125 |
| $H_{max}(M)$(km) | 100 | 86.1 | 87.5 | 102 | 109 | 105 | 105 | 83 | 108 | 101 | 91 | 116 |
| $H_{end}(M)$(km) | 96 | 81.3 | 81.9 | 98 | 100 | 100 | 99 | 77 | 106 | 94 | 81 | <113 |
| $H_{beg}(T)$(km) | 106 | 106.0 | 91.0 | >110 | 109 | 114 | 103 | 89 | 112 | 110 | 96 | 119 |
| $H_{end}(T)$(km) | 98 | 81.0 | 83.9 | 103 | 106 | 103 | 103 | 82 | 106 | 97 | 81 | <112 |
| $H_1$(km) | 100 | 86.8 | 87.0 | 108 | 108 | 106 | 103 | 89 | 110 | 104 | 92 | 116 |
| $H_2$(km) |  | 95.5 |  |  |  |  |  |  |  | 106 |  |  |
| $H_p$(km) |  | 95.5 | 87.0 |  |  |  |  |  |  |  | 92 |  |

[1] Meteor burst at H=83 km.

TABLE 2.—*Data on 48 meteor trains*—Continued

| Meteor No. | 8152 | * | 8666 | 8720* | 8725 | 10754 | 10763 | 10751 | 10774 | 10777 [3] | 10780 | 10793 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 8-3-53 | 8-9-53 | 8-9-53 | 8-13-53 | 8-13-53 | 11-6-54 | 11-6-54 | 11-6-54 | 11-21-54 | 11-21-54 | 11-23-54 | 11-26-54 |
| U.T. | 09:02 |  | 11:05 |  | 07:09 | 10:50 | 11:28 | 11:24 | 08:48 | 09:15 | 12:37 | 10:06 |
| Class | Spor. | Per. | Spor. | Per. | Per. | S. Tau. | S. Tau. | S. Tau. | Spor. | Spor. | Spor. | Spor. |
| Corr. rad. $\alpha$ | 34°2 |  | 347°4 | 51°1 | 43°0 | 54°0 | 54°4 | 53°6 | 117°4 | 161°1 | 143°5 | 148°2 |
| $\delta$ | 55°9 |  | 57°0 | 57°7 | 55°9 | 16°1 | 15°2 | 13°8 | 0°2 | 20°4 | −27°0 | 9°8 |
| $V$(km/sec) | 62 | 60.4 | 61 | 60.1 | 65 | 29 | 31 | 30 | 66 | 69 | 62 | 71 |
| $V_H$(km/sec) | 43 | 41.4 | 51 | 40.8 | 45 | 36 | 38 | 37 | 44 | 39 | 42 | 40 |
| $a$(a.u.) | −7.3 | 25.8 | −1.0 | 10.2 | −3.5 | 1.9 | 2.4 | 2.3 | −5.1 | 3.4 | 50 | 5.7 |
| $e$ | 1.13 | 0.964 | 1.9 | 0.908 | 1.28 | 0.80 | 0.85 | 0.82 | 1.1 | 0.72 | 0.98 | 0.84 |
| $q$(a.u.) | 0.97 | 0.928 | 0.95 | 0.940 | 0.99 | 0.38 | 0.35 | 0.38 | 0.54 | 0.96 | 0.98 | 0.93 |
| $q'$(a.u.) | H | 54.0 | H | 19.5 | H | 3.4 | 4.4 | 4.2 | H | 6.0 | 99 | 10 |
| $\omega$ | 156 | 147.3 | 205 | 147.4 | 164 | 113 | 114 | 111 | 82 | 158 | 348 | 28 |
| $\Omega$ | 131 | 137.4 | 137 | 141.0 | 141 | 44 | 44 | 44 | 59 | 239 | 61 | 64 |
| $i$ | 113 | 113.5 | 93 | 114.0 | 118 | 3.4 | 4.9 | 5.9 | 135 | 160 | 114 | 175 |
| $\epsilon$ | 41 | 38.3 | 58 | 40.5 | 38 | 79 | 79 | 80 | 36 | 12 | 39 | 8.3 |
| $\cos_Z$ | .526 | .820 | .859 | .204 | .510 | .754 | .738 | .626 | .688 | .386 | .504 | .693 |
| $M_{vis}$ | +0.6 | +1.1 | +0.1 | −0.1 | −0.7 | +0.9 | +0.8 | +2.0 | +1.4 | −1.5 | +1.1 | +2.2 |
| Duration (sec) | 1.2 | 1.2 | 1.2 | 1.2 | 6.5 | 2.5 | 6.5 | 8.5 | 1.2 | 6.5 | 1.2 | 1.2 |
| $H_{beg}$(M) (km) | 115 | 113.7 | 112 | >99.4 | 125 | 103 | >105 | 100 | 117 | 117 | 115 | 111 |
| $H_{max}$(M) (km) | 100 | 100.7 | <101 | 98.4 | 109 | 84 | 75 | 78 | 98 | 93 | 97 | 105 |
| $H_{end}$(M) (km) | 97 | 93.9 | <101 | 94.4 | 95 | <81 | <71 | 73 | 89 | 89 | 93 | 101 |
| $H_{beg}$(T) (km) | 111 | 108.8 | 107 | 97.3 | 119 | 99 | 98 | 97 | 119 | 111 | 114 | 113 |
| $H_{end}$(T) (km) | 102 | 95.5 | 98 | <95.2 | 97 | <84 | 76 | 77 | 89 | 90 | 94 | 101 |
| $H_1$ (km) | 108 | 102.2 | 107 |  | 107 | 89 | 91 | 87 | 93 | 109 | 105 | 105 |
| $H_2$ (km) |  |  |  |  | 114 | 96 | 93 |  |  | 97 |  |  |
| $H_p$ (km) |  |  |  |  | 107 |  | 91 | 87 |  | 97 |  |  |

[3] Meteor burst at $H=91$ km.

| Meteor No. | 10786 | 10799 | 10803 | 10808 | 8646* | 8639* | 8649* | 11724 | 11733 [3] | 11746 | 11749 | 11752 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 11–26–54 | 11–30–54 | 12–1–54 | 12–2–54 | 12–12–53 | 12–13–53 | 12–14–53 | 12–19–54 | 12–20–54 | 12–21–54 | 12–30–54 | 12–30–54 |
| U.T. | 10:00 | 09:27 | 12:54 | 08:28 |  |  | 12:11 | 09:54 | 07:49 | 11:19 | 07:47 | 09:02 |
| Class | Spor. | Spor. | Spor. | Spor. | Gem. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. | Spor. |
| Corr. rad. $\alpha$ | 115°.4 | 134°.4 | 169°.4 | 153°.3 | 112°.3 | 152°.4 | 131°.3 | 174°.9 | 144°.7 | 185°.5 | 168°.2 | 182°.3 |
| $\delta$ | −7°.4 | 11°.8 | 45°.6 | 43°.4 | 32°.4 | −43°.2 | −1°.3 | 48°.7 | 30°.4 | 25°.7 | 26°.8 | 20°.0 |
| $V$(km/sec) | 59 | 67 | 63 | 63 | 36.2 | 55.7 | 61 | 55 | 62 | 68 | 66 | 75 |
| $V_H$(km/sec) | 42 | 41 | 43 | 42 | 33.9 | 42.0 | 43 | 40 | 44 | 42 | 44 | 48 |
| $a$(a.u.) | 39 | 7.3 | −39 | 21 | 1.36 | 22.7 | −21 | 5.2 | −4.8 | 32 | −5.7 | −1.7 |
| $e$ | 0.99 | 0.93 | 1.02 | 0.96 | 0.896 | 0.957 | 1.02 | 0.85 | 1.05 | 0.97 | 1.09 | 1.51 |
| $q$(a.u.) | 0.49 | 0.52 | 0.94 | 0.75 | 0.142 | 0.976 | 0.31 | 0.78 | 0.24 | 0.96 | 0.52 | 0.87 |
| $q'$(a.u.) | 77 | 14 | H | 42 | 2.58 | 44.4 | H | 9.6 | H | 64 | H | H |
| $\omega$ | 91 | 89 | 203 | 239 | 324.4 | 332.6 | 112 | 237 | 298 | 197 | 264 | 216 |
| $\Omega$ | 64 | 68 | 250 | 250 | 261.0 | 82.1 | 83 | 268 | 268 | 270 | 279 | 279 |
| $i$ | 113 | 169 | 116 | 122 | 23.4 | 96.7 | 126 | 99 | 130 | 136 | 135 | 147 |
| $\epsilon$ | 44 | 26 | 38 | 37 | 63.1 | 49.8 | 43 | 48 | 44 | 26 | 36 | 24 |
| $\cos z$ | .761 | .809 | .951 | .650 | .984 | .219 | .794 | .960 | .748 | .865 | .592 | .579 |
| $M_{vis}$ | +1.2 | +0.9 | +0.7 | +2.7 | −1.1 | +0.3 | +1.5 | +1.7 | +1.0 | +0.9 | +2.0 | +2.2 |
| Duration (sec) | 6.5 | 1.2 | 8.5 | 1.2 | 6.5 | 2.5 | 1.2 | 2.5 | 18.5 | 2.5 | 1.2 | 4.5 |
| $H_{beg}(M)$(km) | 113 | 110 | 118 | 114 | 102.2 | >111.2 | 116 | 111 | 116 | 109 | 112 | 116 |
| $H_{max}(M)$(km) | 90 | 97 | 103 | 111 | 77.0 | 100.2 | 100 | 102 | 99 | 99 | 103 | 110 |
| $H_{end}(M)$(km) | 83 | 87 | 90 | 108 | 64.1 | 96.8 | 94 | 97 | 93 | 89 | 97 | 105 |
| $H_{beg}(T)$(km) | 115 | 95 | 116 | 114 | 95.2 | 108.8 | 110 | 114 | 115 | 111 | 110 | 114 |
| $H_{end}(T)$(km) | 81 | 89 | 99 | 106 | 73.7 | 96.6 | 102 | 101 | 94 | 90 | 98 | 106 |
| $H$(km) | 90 | 92 | 101 | 113 | 89.0 | [4] 97.9 | 105 | 104 | 106 | 102 | 106 | 111 |
| $H_2$(km) |  |  |  |  | 83.5 | 103.8 |  |  | 98 |  |  |  |
| $H_p$(km) | 90 |  | 101 |  | 93.1 |  |  |  | 98 |  |  |  |

[3] Meteor burst at $H=97.4$ km.

[4] Intensity same at $H_1$ and $H_2$.

## Summary

The analysis of 48 meteor trains photographed with Super-Schmidt cameras indicates the following characteristics of trains: (1) Train formation occurs throughout the meteor region from 70 to 120 km. (2) The frequency of trains is much greater than previously suspected. (3) Train formation is much more efficient at higher meteor velocities. (4) Train meteors exhibit the usual relation between height and velocity. (5) For train meteors with a maximum higher than 85 km, the point of maximum light and the persistent point of the train coincide. The same correlation was shown, at heights above 85 km, by the lower maximum of a double-maximum train. (6) Persistent luminescence lasting about 10 seconds occurs between heights of 110 km and 85 km. The average height is 94 km. (7) The duration of a train depends both on the degree of initial atomic activation by the meteor and on environmental conditions. (8) 75 percent of the train meteors move in retrograde long-period orbits, and the remaining meteors move in direct short-period but highly eccentric orbits.

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## *Abstract*

**Data are presented on the heights, durations, and intensities of 48 meteor trains. The beginning and end points of the meteor trains correlated well with those of the meteor trail. The points of maximum train intensity coincide with the heights of maximum meteor luminosity throughout the life-time of the luminescence, for trail maxima above 85 km. The atmospheric region below this altitude is very unfavorable for the occurrence of long duration trains. The initial formation of a train is much more efficient for high velocity meteors. The relatively longer duration trains show no velocity preference due to a balance between the higher probability of train formation by high velocity, hence high altitude meteors, and the greater probability of persistence for a train formed at lower altitudes by low velocity meteors. About three-fourths of the train meteors move in retrograde long-period orbits and the remaining train meteors with low atmospheric velocities move in direct, short-period, and highly eccentric orbits. The cometary-asteroid criterion suggested by Whipple indicates that all the trains were formed by cometary meteoroids.**