# A SOUTHERN HEMISPHERE RADIO SURVEY OF METEOR STREAMS

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Contents



*Summary*

A radio survey of the orbits of 2200 meteors of radio magnitude $+6$ was made at Adelaide (latitude 35° S.) during 1961. The analysis of the data is fully discussed, together with the accuracy of the results. A method of defining and separating the shower meteors from the sporadic background is given. More than 60 separate radiants were delineated during 13 months of part-time recording. Close attention has been paid to the statistical reality and distinctness of the minor radiants.

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The orbits of 12 streams which possibly give rise to both day-time and night-time showers have been determined. It is suggested that the June Ophiuchids and a new shower observed in December are due to a diffuse stream associated with the lost comet Lexell 1770 I.

The orbit of the December Puppids has been found to be of unusually low eccentricity with an inclination of 70°; it is the first stream to be determined with this type of orbit.

The details of many other streams are given, the majority of which have either not been previously detected or have not previously been resolved from the sporadic background.

## I. Introduction

This paper presents the results pertaining to meteor showers detected during the radio survey of meteor orbits undertaken at Adelaide during 1961. The survey is the first in the southern hemisphere in which the orbits of individual meteors have been calculated. Several surveys of this type have been undertaken in the northern hemisphere at varying magnitudes. Davies and Gill (1960) measured the orbits of over 2000 meteors at radio magnitude $+8$; McCrosky and Posen (1961) analysed the trails of 2500 meteors of magnitude $< +3$ photographed simultaneously from two camera stations; and now Hawkins (1962) is extending radio measurements of meteor orbits to magnitude $+11$. None of these surveys, however, has been able to include radiants south of declination $-20°$. Our observations extend to meteors of radio magnitude $+6$, and include both overdense and underdense meteor trails.

Davies and Gill estimated that showers contributed less than 3% to more than 2000 orbits, compared with a figure of 18% obtained by McCrosky and Posen. In the Adelaide survey it is estimated that about 25% of the meteors are associated with showers. These figures are naturally dependent on just how close an association of orbits is deemed necessary to define a shower, and this subject is discussed more fully with reference to the present survey in Section VII. The streams listed in the present paper were resolved from the sporadic background on a sound statistical basis by direct comparison of individual orbits, giving due consideration to the probable errors of observation. During 13 months of part-time recording more than 60 shower radiants were isolated, over 30 of which can be regarded as "definite". These "definite" streams contributed about 17% of the total number of orbits detected, about 8% being contributed by minor streams, which, statistically, can only be classed as "probable".

The paper is constituted as follows: The observational techniques are discussed in Section II; data processing and analysis are outlined in Sections III and IV. The various corrections that need to be applied to the observed radiant in order to determine the true meteor radiant are discussed in Section V. Details concerning the accuracy of the results and the methods used in isolating the streams from the sporadic background are given in Sections VI and VII. The details of the streams are tabled in Section VIII, and the results briefly compared with previous work in Section IX. A full discussion of the streams of low inclination to the ecliptic that were detected by this survey is given in Section X, with special emphasis on the possibility of a stream being detected as two separate showers in the course of one year. Some other streams are discussed in Section XI, particularly those which can only be observed in the Southern Hemisphere. Section XII contains a brief quantitative discussion of the measures of radiant diameter that were possible from the Adelaide data. The paper is concluded with Section XIII.

## II. Observational Technique

The trail of ionized gas left by the meteor is an effective reflector of r.f. energy at the operating frequency of 27 Mc/s. In the system operating at Adelaide during 1961, four receiving sites were used; receiving sites 2 and 3 are 5 km north and east of receiving site 1, and the fourth is at a distance of 14 km approximately south-east of site 1. The transmitter is 23 km south of site 1. The equipment is a combination of continuous wave and pulse.

The echo received at a ground station as the trail is being formed is analogous to the optical diffraction pattern due to a moving straight edge. The specular reflection point is defined as the point on the trail for which the path length between transmitter, meteor trail, and receiver is a minimum. At any two stations the diffraction waveforms are separated in time by an interval equal to that taken by the meteor to travel between the corresponding points of specular reflection. If the range of any specular reflection point is known, the velocity of the meteor can be calculated from the diffraction waveform (McKinley 1951), and thus the spatial separation of any two points of specular reflection can be determined. This separation depends on the orientation of the meteor trail relative to the spaced receivers, and thus by measuring the time differences between the diffraction waveforms recorded at three receivers sited, say, at the corners of a right-angled triangle, the direction cosines of the meteor trail can be obtained. Figure 1 illustrates the principle of this method of observation. As the velocity of the meteor and the time of occurrence are known, the radiant coordinates and orbital elements can then be calculated.

The diffraction waveforms were observed with a c.w. equipment rather than with the more conventional radar. The c.w. technique has the advantage that oscillations in the diffraction waveform occur both before and after the meteor reaches the point of specular reflection. The analysis is invariably carried out on the waveform prior to the specular reflection point, as the waveform after this is usually distorted by the Doppler beat (McKinley 1951) between the direct ground wave and reflected skywave, and indeed, is often missing entirely, for reasons not fully understood. With the radar technique, on the other hand, oscillations in the diffraction waveform are only observed after the meteor has passed the point of specular reflection. The quality of the diffraction waveform depends to a large extent on the uniformity of the trail already formed, and as this is subject to diffusion and other processes and also to distortion by turbulent winds, we can thus expect the waveforms observed by c.w. equipment to follow the theoretical curves more closely than those observed by radar. However, the reduction of c.w. echoes suffers from two complications that do not apply to the radar technique. The first of these is that the form of the diffraction waveform at each receiver is dependent on the phase of the reflected skywave relative to the direct ground wave received from the transmitter. If the trail is in motion due to upper atmospheric winds this phase angle varies with time by as much as several cycles over the course of the diffraction waveform. Mainstone (1960) has described the principle by which this phase angle can be found from the Doppler beat between the ground wave and reflected skywave and extrapolated back into the diffraction waveform. However, Mainstone used only two points on the diffraction waveform to calculate the velocity, whereas the present author has extended his treatment to utilize all the diffraction maxima and minima in defining both the velocity and the position of the specular reflection point.

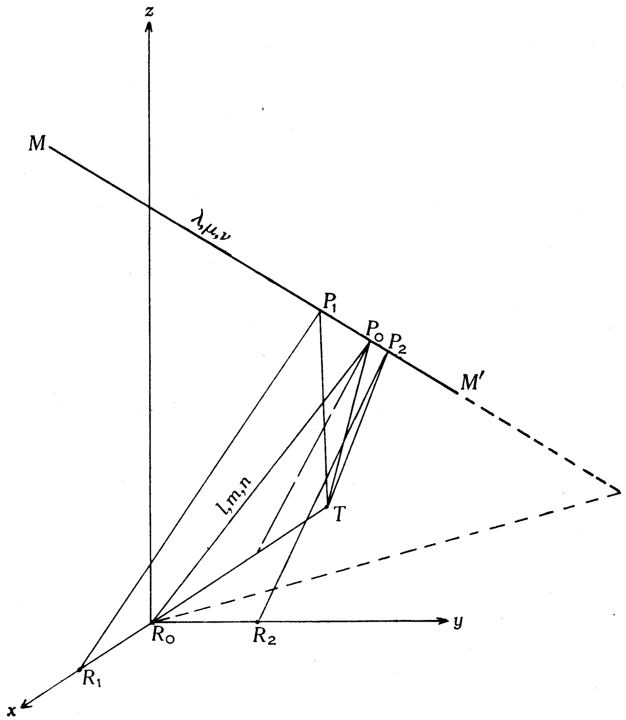


Fig. 1.—The geometry of the Adelaide spaced-station method of determining the direction cosines of a meteor path $MM'$. $T$ is the transmitter, $R_0$, $R_1$, and $R_2$ the three receivers. $P_0$, $P_1$, and $P_2$ are the three corresponding points of specular reflection, defined by the condition that $TP_iR_i$ shall be a minimum.

A theoretical waveform is fitted to all the turning points of the observed waveform by means of a least squares analysis carried out on a digital computor. In this way the meteor velocity and time differences between reflection points can be determined from very poor waveforms. Some of the echoes successfully analysed in this survey showed as few as two Fresnel cycles.

The second complication arising from the use of c.w. instead of radar concerns the geometry involved in determining the direction cosines of the trail from the observed separation of the various specular reflection points. Using the radar system, the ratio of the distance between specular reflection points on the trail to that separating the two corresponding receivers on the ground is very nearly equal to half the cosine of the angle between the direction of the trail and the line joining the two receivers. This holds strictly for independent radar stations and is an adequate approximation where a common transmitter is used at the site of one of the receivers, the latter being spaced only a few kilometres apart.

For the c.w. equipment at Adelaide, however, it was necessary to locate the receivers at least 20 km from the transmitter to limit the amplitude of the direct ground wave. With this separation between the transmitter and receivers, the direction cosines of the trail are not only functions of the separations of the specular reflection points but also of the positions of the specular reflection points relative to the receiving site. This fact can only be ignored at a cost of up to 10% error in the trail direction cosines, hence the echoes reduced for this survey were limited to those for which the position of the reflection point could also be determined from the Doppler beat observed at one of the receivers (Robertson, Liddy, and Elford 1953). This additional information is also applied in the study of upper atmospheric winds, of turbulence, and of the ionization distribution along the trail.

The Adelaide equipment operated with the following characteristics:

c.w. transmitter power = 300 W,
limiting receiver power = $5\times10^{-13}$ W,
c.w. and radar r.f. wavelength = $11\cdot2$ m,
limiting line density = $3\times10^{11}$ electrons/cm,
radar transmitter power = 10 kW,
p.r.f. = 100 p.p.s.

All receiving aerials were $\frac{1}{2}\lambda$ dipoles $\frac{1}{4}\lambda$ above ground; both transmitting aerials were 3-element Yagis directed to the zenith. The equipment is described in detail in a paper by Weiss and Elford (1963).

## III. Data Processing

All recording was done photographically and the echoes used in this survey were read on a Telereader. This film-reading system provides automatic readout facilities onto punched paper tape. The readout accuracy was of the order of $0\cdot1$ ms of echo waveform, which was more than sufficient. The Telereader output was calibrated in terms of the interval between markers on the Doppler beat records, which were locked to the mains supply. Enough measurements were taken over varying times of the day to assure that the mean mains frequency could be taken as 50 c/s exactly. This calibration was done for each month during the survey in order to detect any changes in the camera motor speed, on which the final velocity measurements depended. There was one change during April after the camera motor was rewound, and a 2% slowing down in December 1961 for some as yet unaccountable reason.

In view of the varying waveforms encountered, the author read all the films for the diffraction waveform data. It is interesting to note that even using the automatic readout facilities of the Telereader, the reading limit was little better than 100 echoes per day.

The paper tape output was automatically converted to punched cards and these were collated with Doppler and range data before the data were transferred onto magnetic tape for computation on an I.B.M. 7090 computer.

The records for the months of December 1960 and July 1961 were read twice at widely spaced intervals of time on different film readers in order to estimate the film-reading errors. The quantitative results are discussed in detail in Section VI. They were sufficiently good to be able to accept the bulk of the survey data on one reading.

## IV. Analysis

### (a) *Number of Orbits*

The only echoes accepted for analysis were those with both sufficient Doppler beat to determine the position of one reflection point and sufficiently good Fresnel diffraction waveforms at all three receivers to determine the separations of the specular reflection points. This requirement, together with the low transmitter power, resulted in only 2200 orbits being obtained in 1700 hours operating time.

### (b) *Calculation of Trail Direction Cosines*

Velocities and trail direction cosines were calculated as follows. Consider Figure 1; a meteor trail $MM'$ is illuminated by a transmitter at $T$, the reflected skywave being received at $R_0$, $R_1$, and $R_2$. Let the corresponding specular reflection points on the trail be $P_0$, $P_1$, and $P_2$ respectively, and the times of arrival of the meteor, velocity $V$ km/s, at these points be $t_0$, $t_1$, and $t_2$. Suppose the direction cosines of $R_0P_0$ are $l$, $m$, $n$ and those of the trail $\lambda$, $\mu$, $\nu$.

Write

$$\begin{aligned} TR_0 &= 2d_0, \\ R_0R_1 &= 2d_1, \\ R_0R_2 &= 2c, \\ R_0P_0 &= r_0, \\ T_0P_0R_0 &= 2\rho_0, \end{aligned}$$

and

$$\begin{aligned} \lambda_0 &= V(t_1-t_0)/d_1, \\ \mu_0 &= V(t_2-t_0)/c. \end{aligned} \tag{1}$$

For a radar system, $d_0 \sim d_1 \ll r_0$ and $\lambda_0$, $\mu_0$ are sufficient approximations for the true values $\lambda$, $\mu$.

For the c.w. case, it can be shown that

$$r_0 = \rho_0\left(1-\frac{ld_0}{\rho_0}-\left(\frac{d_0}{\rho_0}\right)^2.(1-l^2)\ldots\right), \tag{2}$$

$$\lambda = \lambda_0\left[1-\frac{l}{r_0}(2d_0+d_1)+\frac{(1-2l^2)}{r_0^2}.(d_1^2+d_1d_0-d_0^2)+\frac{l^2}{r_0^2}(2d_0+d_1)^2\right]-\frac{\lambda_0^3}{r_0^2}(d_0+d_1)^2+O\left(\frac{1}{r_0^3}\right), \tag{3}$$

$$\mu = \mu_0\left[1-\frac{ld_0+mc}{r_0}-\frac{1}{r_0^2}\{d_0^2(1-2l^2)-c^2(1-2m^2)+(ld_0+mc)^2\}\right]$$

$$-\frac{\lambda d_0}{r_0}\left[m-\frac{(ld_0m+c(1-m^2))}{r_0}\right]+O\left(\frac{1}{r_0^3}\right), \tag{4}$$

$$\nu = -(1-\lambda^2-\mu^2)^{\frac{1}{2}}. \tag{5}$$

$V$, $t_0$, $t_1$, and $t_2$ are determined from the Fresnel diffraction wave forms and the radar range $\rho_0$, and $l$ and $m$ are determined independently from the Doppler beat data.

### (c) *Use of Redundant Data*

One advantage of obtaining both the trail direction cosines and the positions of the points of specular reflection is that there is one redundant item of data. This redundancy was used to verify and improve the accuracy of the set of data for each echo in the following manner. The condition of specular reflection requires that

$$\nu = -\mu m + \lambda(l + d_0/r_0)\,.\,\{1-(d_0/r_0)^2\}/n. \tag{6}$$

It is convenient to rearrange (6) to

$$n = -(\mu m + \lambda l')/\nu, \tag{7}$$

where

$$l' = (l + d_0/r_0)\,.\,\{1-(d_0/r_0)^2\},$$

and treat this value of $n$ as the redundant value. We shall denote the value of $n$ obtained from (7) by $n'$, to distinguish it from the value more directly obtained from

$$n = (1-l^2-m^2)^{\frac{1}{2}}. \tag{8}$$

The condition that $n' = n$ can be written

$$\lambda^2(l'^2+n^2)+2\lambda\mu\,.\,l'm+\mu^2(m^2+n^2)-n^2 = 0. \tag{9}$$

From this equation it can easily be shown that the locus of the observed point $(\lambda, \mu)$ is always a real ellipse in the $\lambda\mu$ plane, whose parameters are functions of $l$ and $m$. If $l'$ or $m = 0$, the two axes of the ellipse are $\lambda = \mu = 0$. In practice, the observed values of $\lambda, \mu$ do not exactly satisfy the above equation, and the point $\lambda, \mu$ usually lies a little off the ellipse, say at $P$ in Figure 2.

The value of $n$ calculated from (8) is a more accurate measurement of the true reflection point zenith angle than the redundant value $n'$. Particularly if $\nu$ is small, a small variation in the magnitude of $\lambda$ or $\mu$ can severely affect the value of $\nu$ and hence $n'$. The simplest way to reconcile an observed point $P$ with the theoretical ellipse is to move $P$ towards or away from the centre along the line $OP$. It is necessary to determine how much movement is to be allowed in any particular observation. The ellipse will have a certain error zone defined by the errors in $l$, $m$. Similarly, $P$ will have an error zone defined by the errors in $\lambda, \mu$. Ideally, the point $P$ should be moved to the centre of overlap of the two zones, if this exists, and discarded if the error zones do not overlap. Such a correction was performed in an approximate manner during the analysis. Less than 5% of the echoes had to be discarded. Adjustment of $P$ along $OP$ was made by increasing or decreasing the meteor velocity by a few percent. It can be seen from (1) that this has the effect of adjusting $\lambda$ and $\mu$ in proportion to their absolute values.

A feature of the process outlined above is that it provides a very sensitive measure of the overall accuracy of the velocity reduction technique. Any tendency for the velocities to be too high will result in $n'$ being too large and, as a consequence, the adjustment will tend to always decrease the velocity. Over 13 months the following mean values were obtained for the percentage adjustment of velocity: +1, +1, +0, −0, +0, −0, −0, −0, −1, −0, −0, −0, −0%. It can be seen that there was no systematic adjustment one way or another, thus confirming the average accuracy of the determination of velocity from the diffraction waveforms. In addition, a check was also made to see if there was any correlation between $l$, $m$, and $\Delta V$, where $\Delta V$ is the adjustment in velocity needed to satisfy (9). No correlation was apparent, indicating that the use of the redundant data dealt only with random errors.

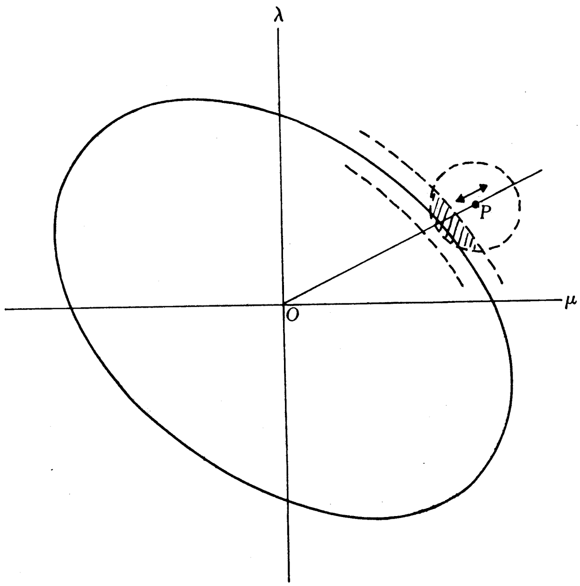


Fig. 2.—Illustrating the use of the redundant data; the ellipse is defined by the direction cosines of $R_0P_0$, $l$, $m$, $n$, and the observed point $P(\lambda, \mu)$ should lie on this ellipse. The velocity is adjusted to move $P$ into the overlapping error zone.

## V. Geocentric Corrections

Before the true radiant can be calculated from the direction cosines of the trail, it is necessary to make allowance for several factors. Corrections to the radiant vector were made for the diurnal motion of the observer, the motion of the trail under the influence of wind shear, retardation of the meteor in the Earth's atmosphere, and finally, for the gravitational attraction of the Earth on the meteor before it enters the atmosphere. This last effect is known as "Zenith attraction", and its application has been fully discussed by Porter (1952).

### (a) *Diurnal Motion of the Observer*

Porter has given the corrections to right ascension and declination necessary to allow for the diurnal motion of the observer. For the present type of survey, however, it is more convenient to correct the geocentric velocity vector outside the atmosphere, $\mathbf{V}_\infty$, for both magnitude and direction before proceeding with the radiant calculation. Consider a true meteor radiant $\vec{R}$, true velocity $\mathbf{V}$, observed velocity $\mathbf{V}'$, as shown in Figure 3. Suppose the motion of the observer, latitude $\phi$, is $\mathbf{v}$, with respect to reference axes $X$, $Y$, $Z$.

$$\mathbf{V}' = \mathbf{V} - \mathbf{v}. \tag{10}$$

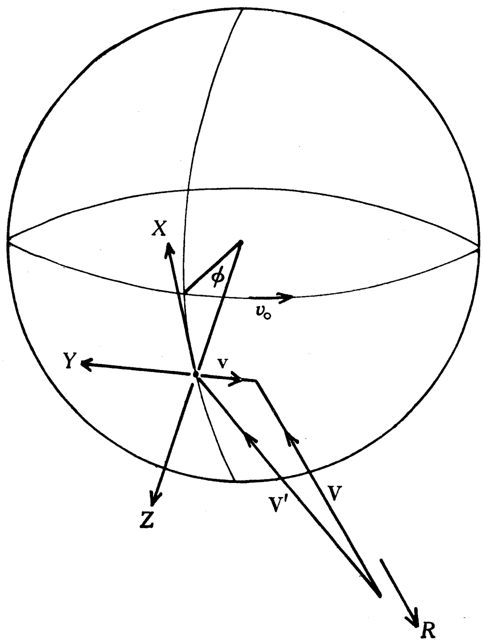


Fig. 3.—Illustrating the correction to the radiant velocity vector for the diurnal motion of the observer. $\mathbf{V}$ is the true velocity, $\mathbf{V}'$ the observed velocity. The motion of the observer is $\mathbf{v}$ with respect to the axes $X$, $Y$, $Z$. $\vec{R}$ is the direction of the true radiant.

Write

$$\mathbf{V} = V\begin{vmatrix}\lambda\\ \mu\\ \nu\end{vmatrix}, \tag{11a}$$

$$\mathbf{V}' = V'\begin{vmatrix}\lambda'\\ \mu'\\ \nu'\end{vmatrix}, \tag{11b}$$

$$\mathbf{v} = \begin{vmatrix}0\\ -\,|v_0\cos\phi|\\ 0\end{vmatrix}, \tag{11c}$$

where $\lambda'$, $\mu'$, $\nu'$ are the observed direction cosines of the meteor path, $\lambda$, $\mu$, $\nu$ the true values, and $v_0$ is the velocity of an observer on the equator. It is easily shown that the true direction cosines are given by

$$\begin{aligned}\lambda &= (V'/V)\,.\,\lambda',\\ \mu &= (V'/V)\,.\,\{\mu'-(0\cdot464\cos\phi)/V'\},\\ \nu &= (V'/V)\,.\,\nu',\end{aligned}\tag{12}$$

and, ignoring second-order terms,

$$V = V'-0\cdot464\cos\phi\,.\,\mu'.\tag{13}$$

One first calculates $V$ from (13) and then applies (12) to obtain the true direction cosines from the observed values.

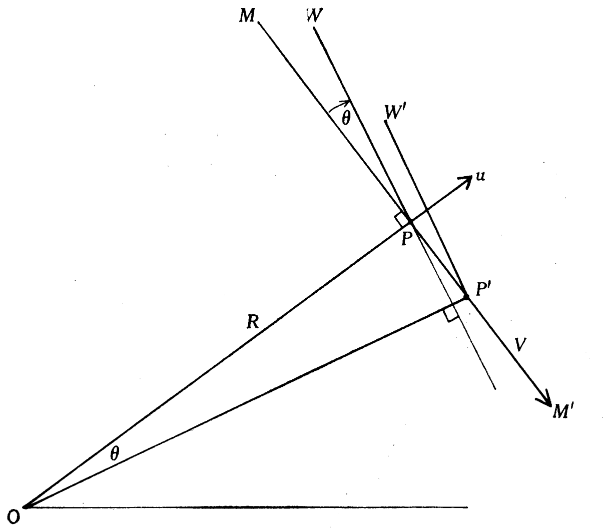


Fig. 4.—Illustrating the motion of a meteor trail $PW$ under the influence of a uniform wind, the line-of-sight component being $u$ m/s. $MM'$ is the path of the meteor, $P$ the specular reflection point for $u = 0$, $P'$ the observed reflection point.

### (b) *Wind Shear*

Normally it is not possible to correct for motion of the trail due to wind shear, but the Adelaide equipment measured the line-of-sight wind velocity at each point of specular reflection. Thus it was possible to correct the position of each reflection point for the corresponding wind velocity. This can be done as follows: in Figure 4, $MM'$ is the path of a meteor, velocity $V$, and $P$ is the geometric specular reflection point relative to the transmitter and receiver at $O$. Let the trail be receding under the action of a uniform wind whose line-of-sight component in the direction $OP$ is $u$ m/s. For simplicity we shall consider the radar case where the transmitter and receiver are coincident rather than the spaced c.w. technique.

If there were no wind the observed specular reflection point would occur at $P$ such that $OP$ is perpendicular to $MM'$. If a steady wind is blowing the ionized trail will lie along $PW$ at the instant the meteor reaches $P$. $PW$ makes an angle $\theta$ to the meteor path such that $\theta = u/V$ and consequently the condition for specular reflection will not be satisfied until the meteor reaches $P'$ where $OP'$ is perpendicular to $P'W'$. The delay of the specular reflection point is approximately $Ru/V$ metres, or

$$Ru/V^2 \text{ seconds.} \tag{14}$$

If the line-of-sight wind velocity is not constant along the trail, i.e. a shear is present, $\theta$ will vary with height, and at any instant the trail will be curved. However, to a first approximation this will not affect the calculated delay of the specular reflection point, as the angle the trail makes with the meteor path at any point is still $\theta = u/V$.

To obtain the true radiant one does not want the direction cosines of the trail $P'W'$, but rather those of the meteor path $MM'$. It can be seen that a wind shear will cause an error in the theoretical time difference between two successive specular reflection points. Suppose the measured times of the observed specular reflection points at two stations are $t_1'$, $t_2'$ and the geometric times appropriate to the path $MM'$ are $t_1$, $t_2$.

$$\Delta t' = t_2' - t_1',$$

$$\Delta t = t_2 - t_1.$$

Hence, neglecting second-order terms,

$$\Delta t = \Delta t' - (R/V^2)(u_2 - u_1), \tag{15}$$

where $u_1$, $u_2$ are the line-of-sight wind components at the observed reflection points. Substituting the distance along the trail, $s = Vt$, (15) can be reduced to

$$\Delta t = \Delta t'(1 - \tfrac{1}{2}\delta), \tag{16}$$

where $\delta = (2R/V)(\mathrm{d}u/\mathrm{d}s)$.

Equation (16) has been derived by Kaiser (1955). For the application in hand, however, it is much better to use (15), as errors in the wind velocity measurements can lead to absurd values of $\delta$ if the specular reflection points are close together. Reasonable values of $\delta$ seldom give rise to corrections for $\Delta t$ greater than 10%.

### (c) *Retardation*

Retardation in the Earth's atmosphere will be discussed elsewhere, but a brief summary of the main facts concerning this correction are given below.

By considering the two conservation equations of Herlofson (1948) applicable to a solid spherical particle, it can be shown that to a first approximation the retardation $\Delta V$ suffered by a meteor by the time it reaches an atmospheric level where the pressure is $p$ kg/m$^2$ is given by

$$\Delta V = V_0 G p/(40 \cos \chi), \tag{17}$$

where $V_0$ is the observed velocity (km/s), $G$ is the surface area/mass ratio (cm$^2$/g), and $\chi$ is the radiant zenith angle. Furthermore, if we assume that the atmosphere is isothermal and that the specular reflection point coincides with the point of maximum ionization, (17) can be reduced to

$$\Delta V = 12l/HV_\infty, \tag{18}$$

where $l$ is the latent heat of vaporization of the meteor, and $H$ is the scale height. Using Jacchias' value of $3\times10^{11}$ ergs/g for $l$, and $5\cdot8$ km for the scale height, (18) reduces to

$$\Delta V = 65/V_\infty, \tag{19}$$

where $\Delta V$, $V_\infty$ are in km/s. Davies and Gill used an equation very similar to this ($\Delta V = 70/V_0$) to correct for retardation, but the results of the Adelaide survey do not agree with the theory outlined above. The values of $\Delta V$ calculated from a more exact form of (17), using the 1959 A.R.D.C. tables for $p$, do not show any correlation with $V$.

In assuming an isothermal atmosphere we have used an expression (Weiss 1959*a*)

$$\rho_{\text{max.}} \propto (\cos\chi)/V_\infty^2, \tag{20}$$

where $\rho_{\text{max.}}$ is the atmospheric density at the height of maximum ionization.

The Adelaide results indicate that the exponent of $V_\infty$ in (20) is $-1$ rather than $-2$. This would account for the lack of correlation of the calculated $\Delta V$ values with $V$. Greenhow and Hall (1960) have drawn attention to the failure of meteors of magnitude $+6$ to evaporate at the heights predicted from photographic observations. If the dependence of the atmospheric pressure at the height of maximum ionization is given by $p_{\text{max.}} \propto V^{-x}$, they found that $1\cdot0 < x < 1\cdot5$, which is in approximate agreement with our results. They concluded that either the high velocity meteors were of much greater density than expected or fragmentation caused the trail to have a large initial radius, resulting in detection only of those meteors which penetrated well below the mean height. Another analysis of their data (Elford, personal communication 1961) suggests that it may be the low velocity meteors evaporating above the predicted heights, that cause the low value of the exponent. Fragmentation of slow meteors would certainly cause the magnitude of the velocity exponent in (20) to fall below the theoretical value, but this cannot be the only factor, as the exponent does not vary greatly with velocity. In view of these results, the corrections applied for retardation which were calculated from a more accurate form of (17) must be treated with considerable caution. Until more is known about fragmentation, however, there seems no alternative to these expressions, and a brief comparison of velocities obtained for some of the well-known showers with photographic results indicates that the calculated values of retardation are at least reasonable.

## VI. Accuracy of Results

The accuracy of the system is primarily governed by the accuracy with which the observed diffraction waveforms can be read from the film records and interpreted. To assess the accuracy of the film reading, and to some extent the reduction procedures, the records for July were read twice. The rereading included the Doppler information, which was read from a separate film record. For the first reading the diffraction data were not read on the Telereader, but on a manual and less accurate film-reader. Thus the second set of data which was used in the final analysis is certainly more accurate. This was verified by various measurements of scatter incorporated in the automatic computing.

Unlike data read from radar system films, two sets of input data for a c.w. diffraction waveform cannot be easily compared, as the origin of measurement and mode of interpretation can be varied arbitrarily by the person reading the films. The test of accuracy lies only in a comparison of the final results for the same meteor. There were 161 meteors in July common to both sets of film-reading. Seven meteors ($< 5\%$) were obviously in error (radiant difference $> 10°$); the distributions for the differences in $\alpha$, $\delta$, and $V_0$ for the remaining 154 meteors are shown in Figure 5. These distributions indicate that the standard errors for the radiant data are: $\alpha$, $\pm 1\cdot 9°$; $\delta$, $\pm 1\cdot 5°$; $V_0$, $\pm 1\cdot 4$ km/s. These figures indicate the expected reading error for

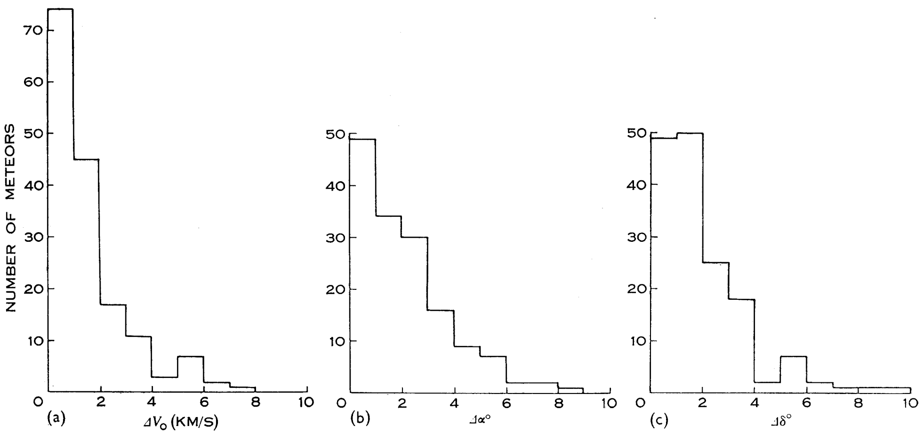


Fig. 5.—The distributions of the differences in radiant data for 154 meteors detected during July 1961, that were read and analysed twice. (*a*) Observed velocity; (*b*) radiant right ascension; (*c*) radiant declination.

meteors for which no gross errors have been made in interpretation, as the very large errors have been excluded from the distributions. We could expect the final survey data to be a little better than this, as it was not only read entirely on the better film-reader, but by this time the author had greater experience in interpreting the diffraction waveforms.

The values for the orbital elements, $e$, $i$, $\omega$, and $1/a$, were compared for 73 meteors and the results are shown in Figure 6. However, the interpretation of these results is not as straightforward as those for the radiant data. For example, the argument of perihelion $\omega$ becomes undefined as $e \rightarrow 0$. The comparison indicates standard errors of the following order: $e$, $\pm 0\cdot 04$; $i$, $\pm 3°$; $\omega$, $\pm 4°$; and $1/a$, $\pm 0\cdot 08$ a.u.$^{-1}$. These results are similar to those estimated by Davies and Gill (1960).

In order to assess the effects of variations of input data on the output, a set of data was programmed with a steady variation of one item of input data for each meteor. The four items of input data varied were:

(1) The phase angle between the direct ground wave and reflected skywave at one receiving station, $\psi$.

(2) The line-of-sight wind velocity at one receiving station, $u$. Besides the shear effect discussed in Section V($b$), this will also affect the extrapolation of $\psi$ back into the diffraction waveform.

(3) Time intervals were simultaneously placed at regular intervals on the three photographic traces in order to determine the time differences between the diffraction waveforms from the three receivers. It was estimated that the standard error in

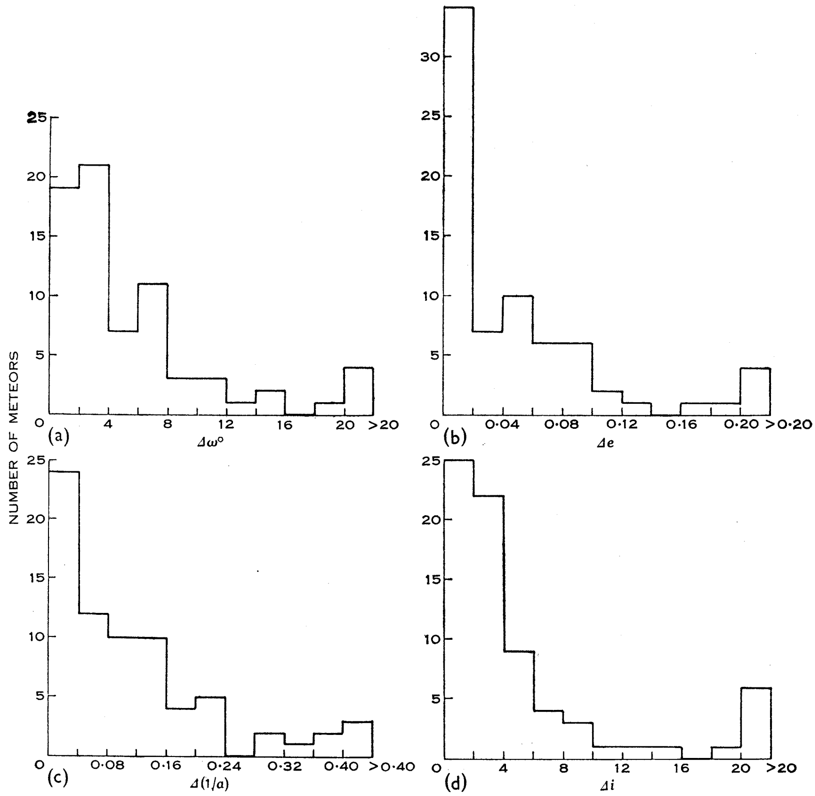


Fig. 6.—The distributions of the differences in orbital data for 73 meteors detected during July 1961, that were read and analysed twice. ($a$) Argument of perihelion; ($b$) eccentricity; ($c$) reciprocal semimajor axis; ($d$) inclination.

noting the relationship of each diffraction waveform to the corresponding time marker, $T$, was about $\frac{1}{2}$ ms.

(4) One of the direction cosines of the line joining the main station receiver to the corresponding specular reflection point on the trail, $l$.

Table 1 lists the variation in output data corresponding to the expected error in each of these items of input. The last row indicates the total error to be expected from these four sources. It can be seen that these figures are similar to those found from the film-reading comparison. The figures in Table 1 suggest that errors will contribute about $3 \cdot 3°$ to the standard deviation of any radiant position, compared to a figure of $2 \cdot 0°$ obtained from the comparison data. A study of the results obtained for the Southern $\delta$-Aquarid and Geminid showers indicates that a standard deviation in radiant position of $2 \cdot 3°$ covers all errors, not just the film-reading errors considered above. This infers that the figure of $3 \cdot 3°$ deduced from Table 1 is an overestimate, and also that factors such as non-uniform ionization along the trail do not seriously affect the results.

## VII. Grouping of Data into Showers

In this section the method which was used to separate the shower orbits from the sporadic background is discussed. We shall first consider the necessary conditions that must be satisfied before any two orbits are classified as "associated", i.e. belonging to a common stream.

Table 1

VARIATION IN OUTPUT CORRESPONDING TO EXPECTED ERROR IN INPUT

| Variation | $\Delta\alpha$ | $\Delta\delta$ | $\Delta V_g$ (km/s) | $\Delta e$ | $\Delta i$ | $\Delta\omega$ | $\Delta(1/a)$ (a.u.$^{-1}$) |
|---|---|---|---|---|---|---|---|
| $\psi \pm 36°$ | $1 \cdot 1°$ | $1 \cdot 2°$ | $0 \cdot 5$ | $0 \cdot 004$ | $5°$ | $0 \cdot 5°$ | $0 \cdot 009$ |
| $u \pm 10$ m/s | $0 \cdot 5$ | $0 \cdot 1$ | $0 \cdot 2$ | $0 \cdot 013$ | $0 \cdot 5$ | 1 | $0 \cdot 019$ |
| $T \pm \frac{1}{2}$ ms | $0 \cdot 5$ | $0 \cdot 3$ | $0 \cdot 2$ | $0 \cdot 002$ | $0 \cdot 1$ | 1 | $0 \cdot 004$ |
| $l \pm 0 \cdot 02$ | $1 \cdot 7$ | $0 \cdot 3$ | $0 \cdot 7$ | $0 \cdot 023$ | 1 | $0 \cdot 3$ | $0 \cdot 024$ |
| Expect | $2 \cdot 9$ | $1 \cdot 6$ | $1 \cdot 2$ | $0 \cdot 03$ | $5 \cdot 7$ | $2 \cdot 5$ | $0 \cdot 04$ |

### (a) *Association of Orbits*

It was decided to make the initial classification of meteors on the basis of the orbital elements, rather than on the radiant coordinates plus geocentric velocity. The use of the orbital elements has the advantage that the parameters are more fundamental, having regard to the initial formation of the streams, and that these parameters generally do not vary with time as markedly as does the radiant position. The four parameters chosen were the reciprocal of the semimajor axis $1/a$, eccentricity $e$, inclination $i$, and true anomaly $\nu$. The longitude of the ascending node $\Omega$ can initially be ignored, as the observations were made over a short period (5–10 days) each month. Only three of the four parameters are independent, owing to the restriction that the Earth's orbit must intersect the meteor orbit. We shall regard the semimajor axis $a$ as the dependent variable, that is,

$$a = a(e,\nu). \tag{21}$$

The disadvantage of using the orbital elements as a basis of classification lies in the fact that the observational errors are not known to the same order of accuracy as for the radiant coordinates. The figures indicated by the comparison data in the last section, however, were taken as a measure of the contribution of observational errors to the standard deviations. Accordingly, the definition of "association" between any two orbits of the same month is that the following conditions are all satisfied:

$$\begin{aligned} |1/a_1-1/a_2| &\leqslant 0\cdot 15,\\ |e_1-e_2| &\leqslant 0\cdot 07,\\ |i_1-i_2| &\leqslant 7°,\\ |\nu_1-\nu_2| &\leqslant 7°. \end{aligned} \tag{22a}$$

These limits are qualified by the condition that, if $e < 0\cdot 3$, the allowable range of $\nu$ is increased to $7°+100(0\cdot 3-e)$. This takes into account the decrease in accuracy with which $\nu$ can be determined as $e \to 0$. In practice, this qualification is not needed, as there were no showers observed for which $e < 0\cdot 4$. All orbits in any group must lie within a total range not exceeding twice the figures given in (22). It is assumed that these limits are adequate to cover the real spatial spread of shower orbits. This assumption in effect defines what we mean by "shower". Any group of meteors belonging to an old stream, which has suffered greater dispersion than these limits allow, will thus be classified as part of the sporadic background.

Since these tests were devised and used, the author has noted that Southworth and Hawkins (1963) have independently carried out a very similar analysis on the orbits of 360 photographic meteors. They defined the difference between two orbits, $A$ and $B$ say, in a five-dimensional orthogonal space as

$$\mathrm{D}(A, B) = \left\{\sum_{j=1,5} c_j^2[C_j(A)-C_j(B)]^2\right\}^{\frac{1}{2}},$$

where $c_j$ are normalizing functions of the orbital elements used in determining the geometry of the space, and $C_j$ are independent functions of the orbital elements chosen to provide suitable measures of each orbital element.

Southworth and Hawkins note that each $c_j$ should be inversely proportional to the expected standard deviation of the corresponding $C_j$ of a stream. For two meteors to be associated, $\mathrm{D}(A, B)$ must be less than a certain value, $D_s$ say; that is,

$$\mathrm{D}(A, B) < D_s. \tag{22b}$$

It can be seen that the association tests given by (22a) also satisfy an expression of the form of (22b). However, the tests of orbital association given by (22a) are basically more stringent in that they require the difference in each orbital element to be less than a specified amount, whereas (22b) only requires that the sum of the differences of all the orbital elements, normalized in a suitable manner, be less than a given total amount.

It should be noted, however, that whereas we have set the limits given in (22a) on the basis of the expected observational errors in each orbital element, Southworth and Hawkins have based their values of $c_j$ on an idealized dispersive mechanism acting on the meteor streams, i.e. they have concluded that the apparent differences $\mathrm{D}(A, B)$ between orbits in a given stream are true differences and not just due to observational error. This difference in approach is reasonable because the expected observational errors in the orbits of the 360 photographic meteors they analysed are about an order of magnitude less than those for the orbits determined in this survey. However, observational errors would certainly have to be taken into account if the same analysis were made on a survey such as that of McCrosky and Posen, where the orbits were not so accurately determined.

Apart from these points, the general approach in both surveys to the problem of resolving minor streams from the sporadic background is very similar.

To return to the Adelaide survey: each orbit in a given month was tested for association with every other orbit with the aid of an I.B.M. 1620 computer. In this manner the orbits could be classified into groups representing major and minor streams. Precautions were taken to ensure that as far as possible major groups were not split into several minor groups. At this stage orbits were not prohibited from contributing

TABLE 2

THE GROUPS COMPILED FOR EACH MONTH OF 1961

| Month | No. of Orbits | $n = 2$ | | $n = 3$ | | $n = 4$ | | $n = 5$ | | $n > 5$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | O* | E | O | E | O | E | O | E | O | E |
| Dec. '60 | 115 | 9 | 6 | 4 | | 4 | | 1 | | 1 | |
| Jan. '61 | 119 | 5 | 8 | 2 | 5 | 0 | | 0 | | 1 | |
| Feb. | 104 | 7 | 6 | 1 | | 0 | 6 | 0 | | 0 | |
| Mar. | 145 | 15 | 14 | 3 | | 0 | | 1 | | 0 | |
| Apr. | 70 | 6 | | 2 | 8 | 1 | | 0 | | 0 | |
| May | 209 | 8 | 16 | 5 | | 2 | | 1 | | 11 | |
| June | 188 | 12 | 14 | 8 | | 3 | | 1 | None | 8 | None |
| July | 36 | 2 | | 0 | 10 | 0 | 6 | 0 | | 0 | |
| July/Aug. | 287 | 13 | 23 | 8 | | 5 | | 3 | | 13 | |
| Aug. | 143 | 10 | 10 | 3 | 9 | 3 | | 0 | | 3 | |
| Sept. | 262 | 18 | 2 | 13 | | 5 | | 2 | | 11 | |
| Oct. | 189 | 11 | 12 | 5 | | 1 | 6 | 2 | | 7 | |
| Nov. | 108 | 5 | 12 | 3 | 6 | 1 | | 1 | | 4 | |
| Dec. '61 | 126 | 11 | | 3 | | 4 | | 1 | | 2 | |
| Total | 2101 | 132 | 142 | 60 | 39 | 29 | 18 | 13 | 0 | 61 | 0 |

* O is the number of groups of $n$ associated orbits initially compiled for each of the 14 sets of real data. E is the number of chance groups expected if the data were random.

to more than one group, as it was recognized that it could prove impossible to determine to which of two neighbouring streams a particular meteor belonged. This point is discussed more fully later in this section.

The numbers of groups compiled in this manner for each month of observation are listed in Table 2. Besides the normal periods of operation in July and August, there was an additional period of observation during the δ-Aquarid shower in late July and early August. This is listed as the July/August set, and it contained the largest group of associated orbits recorded during the survey, initially 42 δ-Aquarid orbits.

### (b) *The Statistical Significance of Small Groups*

Perhaps the most important question to be answered concerns the statistical significance of the groups containing only a few orbits. It is obvious that the large groups would not arise purely by chance, but some measure of the significance of the small groups is necessary if a discussion of the minor showers is to be meaningful. In order to estimate the contribution of chance associations, 14 random sets of data were constructed, having regard to the orbital restriction expressed in (21). These sets were then analysed for groups in exactly the same manner as was used for the real data. These results are given in Table 3. No groups of more than five orbits were obtained for the random data, so it is obvious that almost all the groups from the real data containing six or more orbits are significant. However, the significance of the smaller groups is not immediately apparent. From a consideration of the manner in which groups were obtained, it was possible, using the results of Table 3, to arrive

TABLE 3
THE GROUPS COMPILED FROM RANDOM DATA

| | $N_t$* | $n = 2$ | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 115 | 7 | | | |
| 2 | 119 | 9 | 1 | 1 | |
| 3 | 104 | 6 | 1 | | |
| 4 | 145 | 7 | 2 | | |
| 5 | 70 | 3 | | | |
| 6 | 209 | 20 | 10 | 2 | |
| 7 | 188 | 24 | 2 | 3 | |
| 8 | 36 | 2 | | | |
| 9 | 287 | 28 | 9 | 5 | 1 |
| 10 | 143 | 11 | 3 | 1 | |
| 11 | 262 | 26 | 10 | 4 | 2 |
| 12 | 189 | 18 | 4 | 2 | |
| 13 | 108 | 4 | 1 | | |
| 14 | 126 | 13 | 4 | 1 | |
| Total | 2101 | 178 | 47 | 19 | 3 |

* $N_t$ is the number of orbits in each of the 14 sets of data.

at estimates of the numbers of chance groups expected in the real data as a function of the number of the orbits per group. These estimates are listed in Table 2 alongside the figures for the actual number of groups obtained. The expected numbers have been combined where necessary to give a value of at least 5, so that a $\chi^2$ test could be applied. It appears that there is a significant excess of real groups of 3 and 4 orbits over the number expected by chance. However, the number of chance pairs expected exceeds the number found in practice. Although it is difficult to justify its application, the $\chi^2$ test was applied to the results for $n = 2$, 3, and 4. The excess of groups of 3 and 4 orbits is significant at the 5% level; the observed number of pairs does not differ significantly from the expected distribution.

Approximations made during the course of this analysis were such as to cause an overestimate of the expected number of chance groups. This strengthens the conclusion that many of the groups of 3 and 4 orbits are real. Further evidence to support the significance of the groups of 3 and 4 orbits comes from an examination of the low-inclination streams that intersect the Earth's orbit during the hours of darkness from July to October. This is discussed more fully later in this section.

If the background of sporadic meteors consists of a vast number of unresolved streams we would expect to find an excess of the observed number of pairs of orbits over the number expected by chance, and the number of real groups should increase with decreasing $n$. The fact that this is not observed for $n = 2$ can either be taken as evidence that the sporadic background originated in some different manner to the shower meteors or it can be attributed to overestimation of the number of groups expected by chance. It is difficult to decide between these two possibilities using the Adelaide data alone, although evidence given below does indicate that most of the pairs for the period July–October are due to chance association. Accurately reduced photographic data may provide the necessary evidence, for with this data the association limits can be greatly reduced. The number of groups expected by chance would accordingly be much less, and whether or not there is a real excess of pairs should be easier to determine.

### (c) *Distribution of Meteors with Ecliptic Longitude*

Interesting confirmation of the reality of the groups of 3 and 4 meteors can be obtained from the low-inclination streams which impinge on the Earth during the night-time from July to October. Figure 7 shows the observed distribution of meteors with ecliptic longitude for each month of 1961. The longitude is taken with respect to that of the Apex of the Earth's Way. The anti-Sun component $270° < \lambda_a < 310°$ is particularly prominent during the months of July to October. The combined distribution for these four months is shown in Figure 8(*a*). In order to analyse this component, let us attach to each orbit a number which has one of the following meanings.

(1) $g = 5$ indicates that the orbit contributed to some group containing at least five orbits. These meteors can be regarded as definite shower meteors.

(2) $g = 3$ indicates that the orbit contributed to some group containing three or four orbits, but not to any larger group.

(3) $g = 2$ indicates that the orbit contributed to a pair, but not to any larger group.

Figures 8(*b*), 8(*c*), and 8(*d*) show the distribution with $\lambda_a$ for the above three sets of meteors contributing to the distribution of Figure 8(*a*). Figure 8(*e*) shows the distribution of Figure 8(*a*) less the three sets, i.e. for all meteors not contributing to any group in the 4-month period. This distribution has no significant asymmetry, showing that the excess anti-Sun component apparent in Figure 8(*a*) is almost entirely due to shower meteors. The distribution for the definite shower meteors (Fig. 8(*b*)) shows that all these meteors belong to the Sun and anti-Sun components.

The distribution for $g = 3$ given in Figure 8(*c*) shows that these meteors are predominantly members of showers. Were these groups of three and four meteors due to chance, the distribution for $g = 3$ would be similar to that shown in Figure 8(*e*), with only a slight excess in the region of the anti-Sun. In fact the distribution shows only a few meteors not coming from the direction of the Sun or anti-Sun.

On the other hand, the distribution for those meteors for which $g = 2$ (Fig. 8(*d*)) does not differ significantly from the total distribution less the meteors contributing to groups containing three or more orbits. The latter distribution is almost identical with that shown in Figure 8(*e*). Thus we have evidence indicating that most of the pairs of orbits obtained from the association analysis for these 4 months are due to chance association.

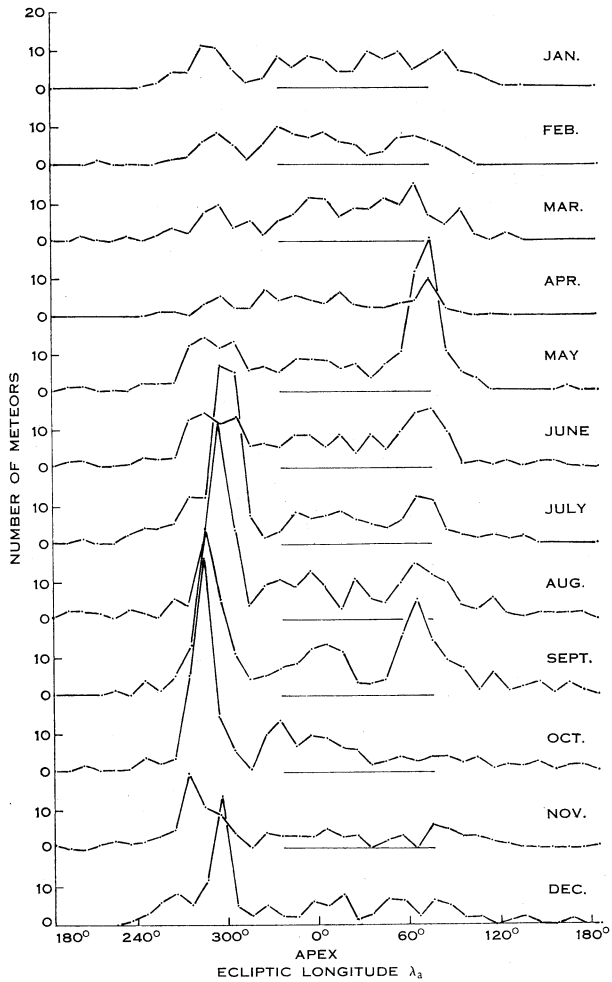


Fig. 7.—The observed distribution of meteors with ecliptic longitude relative to the Apex of the Earth's Way for each month in 1961. The "Sun" peaks are centred on $\lambda_a = 70°$, the "anti-Sun" peaks on $\lambda_a = 290°$.

The conclusion that the prominent anti-Sun component for this period is due to shower meteors raises an interesting point. These streams, providing they are of low inclination, should be visible after perihelion passage as day-time showers. The meteors from these streams should appear to emanate from near the Sun, and a simple calculation shows that they should encounter the Earth during May and June. An inspection of Figure 7 shows that there is, in fact, a very prominent Sun component of meteors during May. Further confirmation is given by the distribution with ecliptic longitude of those meteors in May for which $g = 5$. This is shown in Figure 8($f$). Without exception, they all come from near the Sun. The Sun peak in May thus appears to be due to some of the streams that contribute to the anti-Sun peak from July to October. These low-inclination streams are considered more fully in Section X.

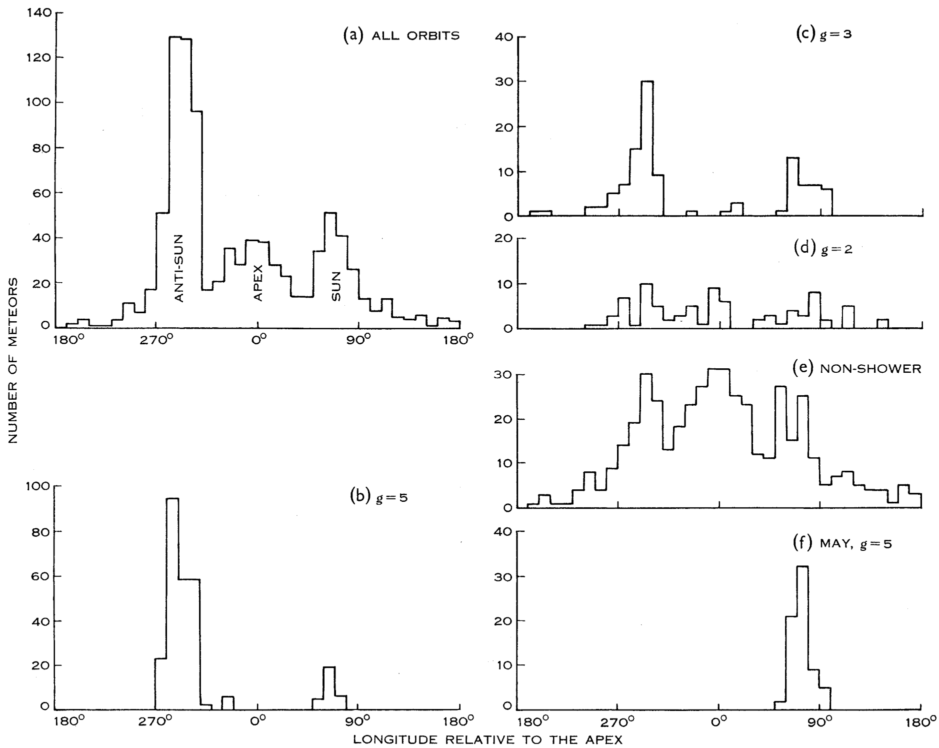


Fig. 8.—The observed distributions of meteors with ecliptic longitude relative to the Apex of the Earth's Way for the four months July–October. ($a$) All orbits; ($b$) orbits contributing to groups for which $n \geqslant 5$; ($c$) orbits contributing to groups for which $n = 3$ or 4; ($d$) orbits contributing to pairs only ($n = 2$); ($e$) orbits not contributing to any group; ($f$) the distribution for May for definite shower echoes, i.e. those contributing to groups for which $n \geqslant 5$.

### ($d$) *The Distinctness of Small Groups*

Apart from the question of the reality of the minor groups, the significance of the separation of two groups with similar orbital elements was considered. In several instances attention was drawn by the number of orbits two groups had in common. These groups were treated in the following manner: if the smaller of two groups had less than 50% of its orbits to itself, it was discounted, and the orbits which were not in common were closely tested for possible membership of the major group. In a few cases orbits were thus accepted as members of a group, although they had initially failed the association tests given in (22). As a result of this scrutiny, only 25 orbits,

Table 4(*a*)

LIST OF RADIANT DATA

| Radiant | $n$ | $\bar{\odot}$ | $\bar{\alpha}$ | $\Delta\alpha^*$ | $\frac{d}{d\odot}(\alpha)$ | $\delta$ | $\Delta\delta^*$ | $\frac{d}{d\odot}(\delta)$ | $\bar{V}_0$ | $\bar{V}_g$ | $\Delta V_g^*$ | $\frac{d}{d\odot}(V_g)$ | Name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60·12·1 | 11 | 259·4 | 109·4 | 0·7 | 1·1 | +30·0 | 1·3 | | 34·3 | 32·5 | 0·8 | | Geminids |
| 12·2 | 4 | 258·6 | 80·0 | 0·5 | 1·3 | +16·8 | 1·6 | | 24·3 | 21·5 | 0·9 | | |
| 12·3 | 4 | 257·6 | 90·9 | 1·3 | | + 8·9 | 2·7 | | 29·1 | 26·9 | 1·0 | | |
| 12·4 | 4 | 260·8 | 112·0 | 2·9 | | +21·7 | 0·6 | | 32·7 | 30·8 | 1·4 | | |
| 12·5 | 3 | 258·8 | 248·0 | 2·5 | | −24·2 | 6·5 | | 29·0 | 26·9 | 0·8 | | Scorpids |
| 12·6 | 3 | 258·1 | 230·6 | 2·3 | | −20·6 | 6·2 | | 33·6 | 31·9 | 1·9 | | |
| 12·7 | 4 | 256·2 | 154·9 | 1·9 | | −60·6 | 4·9 | | 40·4 | 38·9 | 2·1 | | |
| 12·8 | 5 | 258·3 | 138·4 | 2·6 | | −52·9 | 1·9 | | 40·8 | 39·1 | 0·7 | | Puppids |
| 12·9 | 4 | 256·6 | 96·1 | 1·7 | | +15·1 | 1·8 | | 42·1 | 40·6 | 1·5 | | |
| 61· 1·1 | 6 | 299·5 | 133·5 | 0·7 | 1·1 | +14·3 | 3·7 | | 28·3 | 26·7 | 0·8 | | |
| 1·2 | 3 | 299·9 | 117·5 | 1·3 | | + 7·8 | 2·6 | | 25·8 | 24·0 | 1·5 | | |
| 3·1 | 5 | 353·8 | 351·7 | 2·6 | | +12·6 | 1·9 | | 23·2 | 21·7 | 0·1 | +0·2 | |
| 3·2 | 3 | 353·7 | 339·5 | 1·0 | | − 7·6 | 3·4 | | 31·5 | 29·8 | 0·6 | | |
| 3·3 | 3 | 354·5 | 188·5 | 2·3 | | − 3·8 | 1·6 | | 34·3 | 32·8 | 2·0 | | Virginids |
| 4·1 | 4 | 27·6 | 8·4 | 4·9 | | +14·9 | 4·6 | | 31·5 | 29·8 | 2·4 | | |
| 4·2 | 3 | 28·3 | 6·5 | 11·4 | | + 4·3 | 2·6 | | 27·4 | 25·1 | 1·7 | | |
| 5·1 | 18 | 63·9 | 44·3 | 1·1 | 80· | +19·5 | 1·3 | | 29·8 | 28·3 | 0·9 | | ζ-Perseids |
| 5·2 | 11 | 62·1 | 46·5 | 1·3 | 1·0 | +19·1 | 2·1 | | 26·4 | 24·4 | 0·7 | | |
| 5·3 | 10 | 63·7 | 37·0 | 1·0 | 1·7 | +19·8 | 1·5 | | 36·0 | 35·8 | 1·2 | | |
| 5·5 | 6 | 62·3 | 58·8 | 2·0 | 1·2 | +23·7 | 2·0 | | 23·5 | 21·0 | 1·3 | | |
| 5·6 | 9 | 64·0 | 40·6 | 1·1 | 1·4 | + 5·6 | 2·2 | | 31·3 | 30·1 | 1·4 | | |
| 5·8 | 3 | 64·9 | 35·5 | 2·0 | | + 1·0 | 1·0 | | 37·2 | 35·7 | 1·3 | | |
| 5·9 | 6 | 61·9 | 47·8 | 1·0 | 1·9 | + 8·1 | 1·7 | −1·2 | 31·9 | 31·8 | 1·1 | −0·9 | |
| 5·10 | 4 | 60·7 | 255·2 | 2·4 | | −19·1 | 1·7 | | 34·0 | 32·5 | 1·1 | | |
| 5·12 | 3 | 59·0 | 350·3 | 1·7 | | − 3·8 | 3·0 | | 63·1 | 63·5 | 0·7 | | |
| 5·13 | 3 | 61·4 | 23·7 | 3·0 | | +11·5 | 5·4 | | 33·4 | 32·8 | 0·6 | | |
| 6·1 | 7 | 84·6 | 46·6 | 0·4 | 1·5 | +25·0 | 0·7 | | 43·6 | 42·8 | 0·6 | | D. Arietids |
| 6·2 | 8 | 84·8 | 46·1 | 1·1 | | +26·1 | 0·8 | | 39·6 | 38·8 | 1·1 | | D. Arietids |
| 6·3 | 9 | 83·8 | 64·2 | 1·6 | | +25·4 | 2·4 | | 30·2 | 28·4 | 1·3 | | ζ-Perseids |
| 6·4 | 4 | 84·3 | 293·9 | 2·6 | | − 8·4 | 2·5 | | 38·6 | 38·5 | 1·1 | | |
| 6·5 | 7 | 84·2 | 75·5 | 0·9 | 1·0 | +20·3 | 3·1 | | 27·0 | 25·5 | 1·1 | | |
| 6·6 | 4 | 85·9 | 277·7 | 0·4 | 1·3 | −20·0 | 3·0 | | 27·9 | 26·5 | 1·6 | | |
| 6·9 | 3 | 85·3 | 267·2 | 0·7 | | −27·7 | 5·8 | | 25·3 | 23·3 | 1·2 | | Ophiuchids? |
| 6·10 | 3 | 85·0 | 275·2 | 2·9 | | −24·5 | 3·3 | | 31·0 | 31·1 | 1·2 | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7·1 | 48 | 125·8 | 339·4 | 0·4 | 0·9 | −17·3 | 0·3 | 0·2 | 41·2 | 40·8 | 0·4 | | S. δ-Aquarids |
| 7·2 | 3 | 122·0 | 339·4 | 1·9 | | −19·4 | 1·7 | | 43·6 | 43·5 | 1·4 | | |
| 7·3 | 11 | 125·5 | 346·0 | 1·7 | | −19·4 | 1·2 | 0·4 | 34·3 | 33·9 | 1·5 | | S. ι-Aquarids? |
| 7·5 | 3 | 121·2 | 93·7 | 1·5 | | +15·0 | 1·4 | | 43·0 | 44·0 | 0·7 | | |
| 7·6 | 5 | 124·1 | 108·4 | 1·2 | 1·0 | +24·8 | 2·7 | | 32·5 | 33·1 | 0·8 | | |
| 7·8 | 5 | 117·1 | 306·9 | 0·7 | 1·0 | −15·4 | 1·4 | | — | 28·9 | 0·5 | | Capricornids |
| 7·9 | 3 | 121·4 | 319·6 | 4·7 | | − 4·2 | 0·7 | | 35·0 | 36·9 | 1·1 | | |
| 7·11 | 3 | 125·3 | 326·2 | 4·4 | | −12·3 | 6·1 | | 31·5 | 30·0 | 2·5 | | N. ι-Aquarids? |
| 8·1 | 3 | 148·4 | 358·0 | 2·3 | | −11·2 | 1·9 | | 37·2 | 35·9 | 0·8 | | |
| 8·2 | 5 | 146·0 | 343·5 | 3·0 | | + 0·8 | 1·5 | | 27·0 | 25·1 | 1·0 | | |
| 8·3 | 4 | 145·7 | 343·5 | 0·7 | | − 7·2 | 2·9 | | 32·2 | 31·8 | 0·6 | | |
| 8·4 | 4 | 148·0 | 152·7 | 0·7 | 2·1 | +21·0 | 3·9 | | 24·8 | 22·9 | 1·8 | | |
| 8·5 | 3 | 146·2 | 119·7 | 2·3 | | +19·0 | 5·4 | | 43·7 | 43·8 | 1·4 | | |
| 8·6 | 4 | 148·3 | 352·7 | 1·0 | | + 6·3 | 0·6 | | 36·9 | 36·0 | 0·9 | | |
| 9·1 | 19 | 182·3 | 18·1 | 0·8 | 0·7 | + 4·9 | 1·5 | 0·9 | 30·1 | 28·6 | 0·7 | | |
| 9·2 | 9 | 183·6 | 151·7 | 0·9 | | − 0·1 | 1·5 | | 33·2 | 32·2 | 0·6 | −0·5 | Sextanids |
| 9·3 | 5 | 182·6 | 18·6 | 1·2 | 1·4 | +15·3 | 2·9 | | 37·7 | 36·7 | 0·7 | | |
| 9·4 | 9 | 183·5 | 161·5 | 1·5 | | +14·3 | 0·4 | −0·2 | 45·5 | 44·8 | 1·0 | | |
| 9·5 | 7 | 183·7 | 11·0 | 2·5 | | + 4·3 | 2·8 | | 27·6 | 26·8 | 0·7 | | |
| 9·6 | 4 | 182·9 | 19·7 | 1·0 | | + 2·4 | 0·8 | | 31·8 | 31·9 | 1·7 | | |
| 9·7 | 4 | 183·3 | 186·4 | 3·4 | | + 6·1 | 4·6 | | 23·2 | 21·2 | 0·7 | | |
| 9·8 | 3 | 182·7 | 179·0 | 3·0 | | − 8·9 | 3·9 | | 25·7 | 23·2 | 1·1 | | |
| 9·10 | 3 | 181·4 | 31·4 | 7·9 | | +10·0 | 7·9 | | 22·1 | 19·3 | 1·6 | | |
| 9·11 | 3 | 182·1 | 172·0 | 1·6 | | +21·5 | 2·3 | | 32·6 | 31·1 | 1·4 | | |
| 9·12 | 3 | 183·4 | 160·7 | 2·7 | | +11·1 | 0·7 | | 34·4 | 35·4 | 1·4 | | |
| 10·1 | 30 | 213·0 | 44·8 | 0·6 | 0·9 | +12·4 | 1·1 | | 30·2 | 28·8 | 0·6 | | S. Arietids |
| 10·2 | 6 | 212·3 | 96·7 | 0·2 | 1·0 | +14·4 | 1·2 | | 65·3 | 64·7 | 1·1 | | Orionids |
| 10·3 | 6 | 214·1 | 47·8 | 0·7 | 1·1 | + 8·8 | 2·2 | | 32·2 | 33·2 | 1·0 | | |
| 10·4 | 10 | 213·0 | 46·1 | 1·6 | 1·1 | +12·1 | 2·8 | | 24·3 | 22·3 | 1·0 | | |
| 10·6 | 3 | 213·9 | 39·3 | 3·2 | | + 0·2 | 2·5 | | 25·3 | 27·1 | 2·7 | | |
| 10·7 | 3 | 214·3 | 59·0 | 2·6 | | +21·2 | 0·7 | | 34·2 | 35·2 | 3·2 | | |
| 11·1 | 17 | 236·1 | 59·0 | 1·3 | 1·0 | +16·6 | 2·1 | | 25·8 | 23·8 | 0·7 | | S. Taurids |
| 12·1 | 11 | 260·1 | 109·4 | 0·8 | 1·2 | +30·7 | 0·5 | | 34·2 | 33·7 | 0·9 | | Geminids |
| 12·2 | 4 | 253·9 | 94·8 | 0·6 | 1·0 | +14·5 | 1·3 | | 41·6 | 41·3 | 0·8 | | |
| 12·3 | 4 | 253·7 | 245·8 | 3·1 | | −26·2 | 3·4 | | 27·6 | 25·3 | 0·4 | | Scorpids |
| 12·6 | 3 | 256·5 | 143·2 | 2·2 | | −54·1 | 4·5 | | 39·8 | 38·5 | 1·9 | | Puppids |
| 12·7 | 6 | 256·2 | 101·6 | 1·1 | | + 9·6 | 0·7 | −0·5 | 43·0 | 42·2 | 0·8 | | Monocerotids |

* These figures give the 95% confidence limits.

TABLE 4(*b*)

LIST OF ORBITAL DATA

| Radiant | $\overline{1/a}$ | $\Delta \frac{1}{a}^*$ | $\frac{d}{d\odot}\left(\frac{1}{a}\right)$ | $\bar{e}$ | $\Delta e^*$ | $\frac{d}{d\odot}(e)$ | $\bar{i}$ | $\Delta i^*$ | $\frac{d}{d\odot}(i)$ | $\bar{\omega}$ | $\Delta\omega^*$ | $\frac{d}{d\odot}(\omega)$ | $\bar{\Omega}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60·12·1 | 0·84 | 0·04 | | 0·88 | 0·01 | | 16·4 | 2·4 | | 325·7 | 1·5 | | 259·4 |
| 12·2 | 0·54 | 0·04 | | 0·70 | 0·03 | | 4·6 | 1·1 | | 93·7 | 1·4 | | 78·6 |
| 12·3 | 0·61 | 0·03 | | 0·77 | 0·02 | | 15·7 | 2·8 | | 114·3 | 3·5 | | 77·6 |
| 12·4 | 0·99 | 0·05 | | 0·88 | 0·03 | | 0·4 | 0·2 | | 150·3 | 4·5 | | 80·8 |
| 12·5 | 0·44 | 0·06 | | 0·81 | 0·01 | | 5·6 | 4·4 | | 255·4 | 5·6 | | 78·8 |
| 12·6 | 0·74 | 0·07 | | 0·86 | 0·03 | | 8·4 | 3·2 | | 221·1 | 3·2 | | 78·1 |
| 12·7 | 0·34 | 0·13 | | 0·69 | 0·12 | | 66·6 | 5·4 | | 323·7 | 1·7 | | 76·2 |
| 12·8 | 0·48 | 0·07 | | 0·53 | 0·07 | | 70·1 | 2·1 | | 353·4 | 4·0 | | 78·3 |
| 12·9 | 0·05 | 0·10 | | 0·99 | 0·02 | | 18·7 | 3·3 | | 131·5 | 4·4 | | 76·6 |
| 61· 1·1 | 0·62 | 0·06 | | 0·77 | 0·02 | | 4·9 | 2·4 | | 116·7 | 1·9 | | 119·5 |
| 1·2 | 0·33 | 0·10 | | 0·81 | 0·06 | | 9·9 | 2·1 | | 84·7 | 2·2 | | 119·9 |
| 3·1 | 0·34 | 0·05 | | 0·79 | 0·03 | | 9·7 | 1·5 | | 101·3 | 3·1 | | 353·8 |
| 3·2 | 0·47 | 0·02 | | 0·86 | 0·01 | | 2·5 | 2·2 | | 59·7 | 1·3 | | 353·7 |
| 3·3 | 0·42 | 0·05 | | 0·89 | 0·03 | | 2·9 | 1·1 | | 304·3 | 5·5 | | 354·5 |
| 4·1 | 0·41 | 0·07 | | 0·86 | 0·04 | | 12·8 | 5·2 | | 64·9 | 4·6 | | 27·6 |
| 4·2 | 0·85 | 0·10 | | 0·76 | 0·03 | | 5·8 | 3·4 | | 48·6 | 2·4 | | 28·3 |
| 5·1 | 0·58 | 0·03 | | 0·82 | 0·02 | | 4·4 | 1·1 | | 56·8 | 2·0 | | 63·9 |
| 5·2 | 0·64 | 0·03 | | 0·75 | 0·02 | | 2·9 | 1·1 | | 64·8 | 2·2 | | 62·1 |
| 5·3 | 0·41 | 0·06 | | 0·93 | 0·02 | | 10·2 | 2·8 | −2·0 | 42·6 | 2·8 | | 63·7 |
| 5·5 | 0·48 | 0·03 | | 0·71 | 0·03 | | 2·7 | 1·3 | | 89·5 | 3·1 | | 62·3 |
| 5·6 | 0·72 | 0·07 | | 0·84 | 0·02 | | 16·7 | 3·8 | | 224·1 | 2·6 | | 244·0 |
| 5·8 | 0·71 | 0·06 | | 0·91 | 0·01 | | 33·8 | 2·1 | | 212·5 | 0·7 | | 244·9 |
| 5·9 | 0·31 | 0·09 | | 0·89 | 0·03 | −0·0 | 12·5 | 1·9 | 1·6 | 243·7 | 2·0 | +1·9 | 241·9 |
| 5·10 | 0·43 | 0·04 | | 0·89 | 0·01 | | 6·0 | 3·3 | | 305·9 | 3·6 | | 60·7 |
| 5·12 | 0·36 | 0·06 | | 0·80 | 0·03 | | 174·1 | 2·6 | | 270·4 | 2·6 | | 239·0 |
| 5·13 | 0·99 | 0·05 | | 0·92 | 0·01 | | 15·5 | 3·3 | | 22·8 | 1·5 | | 61·4 |
| 6·1 | 0·44 | 0·04 | | 0·98 | 0·00 | | 38·9 | 1·3 | −5·1? | 20·3 | 1·3 | | 84·6 |
| 6·2 | 0·67 | 0·07 | | 0·96 | 0·01 | | 33·4 | 1·7 | | 23·0 | 2·3 | | 84·8 |
| 6·3 | 0·60 | 0·04 | | 0·82 | 0·02 | | 5·7 | 2·2 | | 55·4 | 2·7 | | 83·8 |
| 6·4 | 0·62 | 0·08 | | 0·93 | 0·02 | | 40·1 | 4·4 | | 328·9 | 2·1 | | 84·3 |
| 6·5 | 0·46 | 0·05 | | 0·79 | 0·03 | | 3·7 | 1·9 | | 255·1 | 1·8 | | 264·2 |
| 6·6 | 0·58 | 0·07 | | 0·78 | 0·04 | | 4·5 | 1·7 | | 296·6 | 1·2 | | 85·9 |
| 6·9 | 0·48 | 0·06 | | 0·75 | 0·04 | | 5·0 | 2·3 | | 97·0 | 0·7 | | 265·3 |
| 6·10 | 0·30 | 0·10 | | 0·90 | 0·03 | | 4·1 | 0·1 | | 113·7 | 2·9 | | 265·0 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7·1 | 0·43 | 0·02 | | 0·97 | 0·00 | −0·0 | 32·5 | 1·3 | | 152·4 | 0·8 | −0·5 | 305·8 |
| 7·2 | 0·38 | 0·10 | | 0·98 | 0·01 | | 50·5 | 5·7 | | 155·0 | 2·8 | | 302·0 |
| 7·3 | 0·93 | 0·09 | | 0·90 | 0·02 | | 35·5 | 3·2 | | 153·6 | 2·1 | | 305·5 |
| 7·5 | 0·12 | 0·06 | | 0·99 | 0·00 | | 32·8 | 2·1 | | 211·6 | 3·5 | | 301·2 |
| 7·6 | 0·40 | 0·04 | | 0·90 | 0·01 | | 5·1 | 3·3 | | 53·2 | 2·7 | | 124·1 |
| 7·8 | 0·35 | 0·04 | | 0·87 | 0·02 | | 3·9 | 0·8 | | 289·8 | 2·1 | | 117·1 |
| 7·9 | 0·28 | 0·06 | | 0·95 | 0·01 | | 21·8 | 2·0 | | 311·2 | 5·5 | | 121·4 |
| 7·11 | 0·64 | 0·11 | | 0·85 | 0·04 | | 6·9 | 2·2 | | 312·5 | 2·5 | | 125·3 |
| 8·1 | 0·56 | 0·01 | | 0·92 | 0·01 | | 23·8 | 2·6 | | 143·2 | 3·2 | | 328·4 |
| 8·2 | 0·83 | 0·07 | | 0·75 | 0·02 | | 7·9 | 2·6 | | 310·4 | 3·5 | | 146·0 |
| 8·3 | 0·46 | 0·06 | | 0·89 | 0·01 | | 3·8 | 1·6 | | 127·5 | 3·7 | | 325·7 |
| 8·4 | 0·42 | 0·04 | | 0·75 | 0·04 | | 7·5 | 2·8 | | 90·6 | 4·8 | | 148·0 |
| 8·5 | 0·20 | 0·05 | | 0·99 | 0·01 | | 21·1 | 2·4 | | 206·5 | 3·6 | | 326·2 |
| 8·6 | 0·64 | 0·06 | | 0·93 | 0·01 | | 22·4 | 2·4 | | 328·2 | 2·0 | | 148·3 |
| 9·1 | 0·61 | 0·03 | | 0·83 | 0·01 | | 5·4 | 1·2 | | 125·7 | 1·8 | | 2·3 |
| 9·2 | 0·89 | 0·03 | 0·0 | 0·87 | 0·01 | | 21·8 | 2·3 | | 213·2 | 2·1 | | 3·6 |
| 9·3 | 0·28 | 0·05 | | 0·95 | 0·02 | | 14·8 | 5·4 | | 312·9 | 3·4 | | 182·6 |
| 9·4 | 0·06 | 0·04 | | 0·99 | 0·00 | | 24·8 | 2·3 | | 31·9 | 4·0 | | 183·5 |
| 9·5 | 0·44 | 0·06 | | 0·82 | 0·02 | | 4·2 | 1·6 | | 108·1 | 3·1 | | 3·7 |
| 9·6 | 0·40 | 0·10 | | 0·89 | 0·03 | | 8·4 | 0·2 | −0·7 | 123·9 | 2·2 | | 2·9 |
| 9·7 | 0·49 | 0·08 | | 0·70 | 0·04 | | 5·8 | 3·3 | | 92·9 | 8·3 | | 183·3 |
| 9·8 | 0·39 | 0·08 | | 0·77 | 0·03 | | 6·3 | 3·3 | | 272·6 | 7·6 | | 2·7 |
| 9·10 | 1·24 | 0·09 | | 0·67 | 0·02 | | 8·6 | 0·8 | | 146·4 | 4·3 | | 1·4 |
| 9·11 | 0·53 | 0·06 | | 0·83 | 0·03 | | 23·2 | 1·7 | | 59·9 | 3·2 | | 182·1 |
| 9·12 | 0·62 | 0·04 | | 0·92 | 0·02 | | 7·0 | 2·2 | | 35·6 | 2·6 | | 183·4 |
| 10·1 | 0·50 | 0·02 | | 0·83 | 0·01 | | 5·9 | 1·1 | | 118·3 | 1·6 | | 33·0 |
| 10·2 | 0·16 | 0·11 | | 0·92 | 0·05 | | 160·3 | 2·6 | | 90·9 | 4·0 | | 32·3 |
| 10·3 | 0·28 | 0·04 | | 0·92 | 0·01 | | 13·1 | 3·1 | | 118·6 | 3·0 | | 34·1 |
| 10·4 | 0·80 | 0·05 | | 0·68 | 0·02 | | 5·7 | 2·1 | | 119·3 | 3·0 | | 33·0 |
| 10·6 | 0·27 | 0·10 | | 0·86 | 0·06 | | 13·9 | 3·5 | | 94·0 | 3·4 | | 33·9 |
| 10·7 | 0·68 | 0·09 | | 0·92 | 0·04 | | 2·4 | 1·9 | | 329·0 | 5·4 | | 214·3 |
| 11·1 | 0·48 | 0·03 | | 0·76 | 0·02 | | 4·2 | 1·1 | | 99·0 | 2·9 | | 56·1 |
| 12·1 | 0·75 | 0·05 | | 0·89 | 0·01 | | 18·5 | 1·4 | | 324·5 | 1·3 | | 260·1 |
| 12·2 | 0·09 | 0·07 | | 0·99 | 0·01 | | 22·6 | 2·7 | | 135·3 | 1·9 | | 73·9 |
| 12·3 | 0·42 | 0·07 | | 0·79 | 0·03 | | 4·0 | 3·4 | | 262·6 | 3·3 | | 73·7 |
| 12·6 | 0·53 | 0·06 | | 0·48 | 0·06 | | 69·6 | 5·3 | | 340·5 | 2·6 | | 76·5 |
| 12·7 | 0·18 | 0·11 | | 0·98 | 0·01 | | 39·0 | 4·0 | | 138·9 | 2·0 | −2·7 | 76·2 |

* These figures give the 95% confidence limits.

from a total of nearly 500 shower orbits, were held as members of more than one stream.

The groups were then tested statistically for distinctness. The mean orbit of each group was compared with all the groups in the month under consideration. Using the estimates of standard deviation from the comparison data, the Student's $t$-test was applied to each of the four mean orbital elements, $1/a$, $e$, $i$, and $\nu$. It was found on this basis that no two groups were close enough to warrant pooling the data. It was decided to err on the conservative side in listing the many minor radiants and, as the standard deviations of the orbital elements had probably been underestimated by the comparison data, these values were doubled. In this manner 12 minor groups were absorbed into larger groups. The test was then extended to allow for the possibility that a stream might extend over two months, and thus be detected as two separate groups. The $\zeta$-Perseid stream is a case in point, appearing in the data of both May and June. The data for each month were not combined, however, and the $\zeta$-Perseids have been listed separately in Section VIII as radiants 5·1 and 6·3.

### (e) *Use of Radiant Data*

We have shown that every group of associating orbits containing at least five members almost certainly represents a real stream, whereas those of only three or four orbits may be due to chance association. The radiant data can be used to further test the reality or otherwise of these minor groups. From an inspection of the groups of five or more orbits, it is apparent that the spread in radiant coordinates (see Section XII) for the real streams does not usually exceed by any large amount that expected from a point radiant. Thus we can infer that the minor groups which show a large radiant scatter are probably due to chance association of the orbital data, whereas those with a well-defined radiant position are more likely to be real. This assumption will exclude the real minor groups that have in fact suffered a large degree of dispersion, but the line has to be drawn somewhere, and it is probable that if this restriction were relaxed, the number of chance groups admitted to the realm of "probable showers" would severely reduce the value of our list. In this way 16 groups containing only 3 or 4 orbits were discounted from a total of 50 groups. This proportion is not inconsistent with the figures in Table 2 for the numbers of groups expected by chance, if one remembers that the latter have probably been overestimated.

The radiant data for the large groups were also studied in order to remove any meteors that showed an obvious discrepancy in radiant position. Thus, in the complete analysis, both orbital and radiant data were used to define the showers.

## VIII. List of Showers

All the groups which contain at least three orbits ($n \geqslant 3$) that were compiled in the manner discussed in the last section are listed in Table 4($a$). Those groups which were rejected by the arguments of Section VII($d$) and Section VII($e$) have not been included. The corresponding orbital data are listed in Table 4($b$). The 95% confidence limits are given for each mean parameter; if any parameter showed a significant correlation with solar longitude, the rate of change of the parameter with solar longitude is also given. Each compiled group has been assigned a reference number, the first figure of which indicates the month of observation and the second merely indicates the order in which the groups were originally compiled. Observations were made during both December 1960 and December 1961, so to avoid confusion the groups compiled for 1960 are prefixed by the year. Table 4(*a*) also lists the number of meteors, *n*, contributing to each group. Thus from Table 4(*a*), we see that 6 meteors contributed to group 1·1 in January, and the mean radiant data are

$$\begin{aligned}\alpha &= 133\cdot5\pm0\cdot7+1\cdot1(\odot-299\cdot5)^\circ,\\ \delta &= +14\cdot3\pm3\cdot7^\circ,\\ V_0 &= 28\cdot3\ \text{km/s},\\ V_g &= 26\cdot7\pm0\cdot8\ \text{km/s}.\end{aligned}$$

Table 4(*b*) is set out in a similar manner.

The data for December were more closely studied than those for the other months, as 2 years' records were available. There are several small groups which appear in the data for both years but which show too much scatter in the orbital data to have been compiled by the association analysis discussed in the last section. The reality of these groups, which were excluded by our definition of a shower, confirms the suspicion that some real groups have been excluded from Table 4. However, as has been previously explained, this is unavoidable if any significant degree of confidence is to be placed on those minor groups which are finally accepted.

Table 5

DATA FOR GROUP 7·8

| Meteor | $\alpha$ | $\delta$ | $V_g$ | $a$ | $e$ | $i$ | $\omega$ | $\Omega$ | $\pi$ | $q$ | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8085 | 305 | −17 | 27·9 | 2·5 | 0·84 | 3 | 290 | 114 | 45 | 0·39 | Harvard |
| 8109 | 308 | −15 | 28·5 | 2·8 | 0·86 | 5 | 289 | 118 | 47 | 0·39 | Harvard |
| 8110* | 310 | −13 | 29·2 | 2·6 | 0·86 | 5 | 294 | 118 | 52 | 0·36 | Harvard |
| 79747 | 302 | −17 | 29·4 | 3·3 | 0·88 | 3 | 288 | 112 | 41 | 0·39 | Adelaide |
| 84495 | 312 | −15 | 29·3 | 3·5 | 0·89 | 3 | 287 | 122 | 49 | 0·39 | Adelaide |

* Meteor 8110 was classified as a member of the S. $\iota$-Aquarid stream, but the value of 52° for the longitude of perihelion, $\pi$, does not support this classification.

The extra groups in December, which have been included in Table 4, are 60·12·7–9 and 61·12·6–7. The reality of the groups 60·12·8 and 60·12·9 is confirmed by the two corresponding groups, 61·12·6 and 61·12·2 respectively, in the 1961 data. The former pair can be identified with the poorly determined Puppid shower (Weiss 1960*b*). The group 60·12·7 is supported by the detection of a similar orbit in 1961, which has been included in the data. The group 61·12·7 corresponds well to the Monocerotid shower listed by Whipple and Hawkins. Two meteors from this radiant were also detected in 1960.

The group 7·8 is another group not compiled in the normal way. Two meteors in July, numbers 79747 and 84495, were noticed to compare closely with three from the list of photographic meteors of magnitude brighter than +3 recently published by McCrosky and Posen (1961). The five orbits are listed in Table 5.

TABLE 6

LIST OF SHOWER RADIANTS

| Group | Dates of Detection | $\bar{\alpha}$ | $\bar{\delta}$ | $\bar{V}_g$ (km/s) | Name |
|---|---|---|---|---|---|
| | Dec. | | | | |
| 60·12·1 | 9–13 | 109° | +30° | 33 | Geminids |
| 12·2 | 7–12 | 80 | +17 | 22 | |
| 12·3 | 7–12 | 91 | + 9 | 27 | |
| 12·4 | 12–13 | 112 | +22 | 31 | |
| 12·5 | 9–12 | 248 | −24 | 27 | Scorpids |
| 12·6 | 8–12 | 231 | −21 | 32 | |
| 12·7 | 7–9 | 155 | −61 | 39 | |
| 12·8 | 8–11 | 139 | −53 | 39 | Puppids |
| 12·9 | 8–12 | 96 | +15 | 41 | |
| | Jan. | | | | |
| 61· 1·1 | 16–22 | 134 | +14 | 27 | |
| 1·2 | 18–21 | 118 | + 8 | 24 | |
| | Mar. | | | | |
| 3·1 | 11–16 | 352 | +13 | 22 | |
| 3·2 | 12–16 | 340 | − 8 | 30 | |
| 3·3 | 13–16 | 189 | − 4 | 33 | Virginids |
| | Apr. | | | | |
| 4·1 | 13–30 | 8 | +15 | 30 | |
| 4·2 | 13–29 | 6 | + 4 | 25 | |
| | May | | | | |
| 5·1 | 19–28 | 44 | +20 | 28 | ζ-Perseids |
| 5·2 | 19–28 | 46 | +19 | 24 | |
| 5·3 | 20–28 | 37 | +20 | 36 | |
| 5·5 | 19–27 | 59 | +24 | 21 | |
| 5·6 | 20–28 | 41 | + 6 | 30 | |
| 5·8 | 23–28 | 36 | + 1 | 36 | |
| 5·9 | 19–26 | 48 | + 8 | 32 | |
| 5·10 | 19–25 | 255 | −19 | 33 | |
| 5·12 | 19–21 | 350 | − 4 | 64 | |
| 5·13 | 20–25 | 24 | +12 | 33 | |
| | June | | | | |
| 6·1 | 15–17 | 47 | +25 | 43 | D. Arietids |
| 6·2 | 14–17 | 46 | +26 | 39 | D. Arietids |
| 6·3 | 13–16 | 64 | +25 | 28 | ζ-Perseids |
| 6·4 | 13–19 | 294 | − 8 | 39 | |
| 6·5 | 12–18 | 76 | +20 | 26 | |
| 6·6 | 13–19 | 278 | −20 | 27 | |
| 6·9 | 16–17 | 267 | −28 | 23 | Ophiuchids? |
| 6·10 | 15–18 | 275 | −25 | 31 | |
| | July | | | | |
| 7·1 | 23–04 | 339 | −17 | 41 | S. δ-Aquarids |
| 7·2 | 23–26 | 339 | −19 | 44 | |
| 7·3 | 23–04 | 346 | −19 | 34 | S. ι-Aquarids? |
| 7·5 | 23–25 | 94 | +15 | 44 | |
| 7·6 | 24–01 | 108 | +25 | 33 | |
| 7·8 | 14–25 | 307 | −15 | 29 | Capricornids |
| 7·9 | 22–02 | 320 | − 4 | 37 | |
| 7·11 | 25–03 | 326 | −12 | 30 | N. ι-Aquarids |

TABLE 6 (*Continued*)

| Group | Dates of Detection | $\bar{\alpha}$ | $\delta$ | $\bar{V}_g$ (km/s) | Name |
|---|---|---|---|---|---|
| | Aug. | | | | |
| 8·1 | 18–23 | 358 | −11 | 36 | |
| 8·2 | 16–24 | 344 | + 1 | 25 | |
| 8·3 | 17–20 | 344 | − 7 | 32 | |
| 8·4 | 18–22 | 153 | +21 | 23 | |
| 8·5 | 17–22 | 120 | +19 | 44 | |
| 8·6 | 20–23 | 353 | + 6 | 36 | |
| | Sept. | | | | |
| 9·1 | 22–29 | 18 | + 5 | 29 | |
| 9·2 | 24–29 | 152 | − 0 | 32 | Sextanids |
| 9·3 | 23–29 | 19 | +15 | 37 | |
| 9·4 | 23–29 | 162 | +14 | 45 | |
| 9·5 | 25–29 | 11 | + 4 | 27 | |
| 9·6 | 24–29 | 19 | + 2 | 32 | |
| 9·7 | 23–29 | 187 | + 6 | 21 | |
| 9·8 | 22–25 | 179 | − 9 | 23 | |
| 9·10 | 22–27 | 31 | +10 | 19 | |
| 9·11 | 23–26 | 172 | +22 | 31 | |
| 9·12 | 23–28 | 161 | +11 | 35 | |
| | Oct. | | | | |
| 10·1 | 20–31 | 45 | +12 | 29 | S. Arietids |
| 10·2 | 24–30 | 97 | +14 | 65 | Orionids |
| 10·3 | 20–31 | 48 | + 9 | 33 | |
| 10·4 | 21–30 | 46 | +12 | 22 | |
| 10·6 | 23–30 | 39 | + 0 | 27 | |
| 10·7 | 26–30 | 59 | +21 | 35 | |
| | Nov. | | | | |
| 11·1 | 16–23 | 59 | +17 | 24 | S. Taurids |
| | Dec. | | | | |
| 12·1 | 11–14 | 109 | +31 | 34 | Geminids |
| 12·2 | 5–10 | 95 | +15 | 41 | |
| 12·3 | 5–7 | 246 | −26 | 25 | Scorpids |
| 12·6 | 7–10 | 143 | −54 | 39 | Puppids |
| 12·7 | 5–12 | 102 | +10 | 43 | Monocerotids |

Table 6 has been compiled for quick reference. It gives the radiant position and observed velocity, along with the dates of detection, for all the showers listed in Table 4. The name is given if a shower has been previously listed by others.

## IX. Comparison with Other Results

In order to check for any consistent error in the Adelaide results, the radiant data for the well-known showers have been compared with the data listed by McKinley (1961) and Whipple and Hawkins (1959). There is no significant systematic difference. However, the differences in radiant data for some of the showers treated individually are interesting. The δ-Aquarids in July and August, and the Geminids in December are two well-known showers which have been studied extensively. We shall first consider the former, as it is probably the most intense shower incident on the Southern Hemisphere at the present time.

We have found the radiant coordinates to be

$$\alpha = 339\cdot4\pm0\cdot4+0\cdot9(\odot-125\cdot8)^\circ,$$
$$\delta = -17\cdot3\pm0\cdot3+0\cdot2(\odot-125\cdot8)^\circ.$$

Weiss (1960*a*) has made a careful study of the shower using a radar radiant equipment at Adelaide. He found the coordinates to be

$$\alpha = 342\cdot2+0\cdot8(\odot-126\cdot0)^\circ,$$
$$\delta = -16\cdot6+0\cdot2(\odot-126\cdot0)^\circ.$$

He estimated his error to be $\sim 0\cdot5^\circ$, so the discrepancy in $\alpha$ is significant. McIntosh (1934), using visual observations made in New Zealand between 1926 and 1933, found a mean position for the radiant similar to that obtained by Weiss, but determined the daily motion as $0\cdot96^\circ$ in $\alpha$ and $0\cdot41^\circ$ in $\delta$. However, Whipple and Hawkins have listed the radiant as $\alpha = 339^\circ$, $\delta = -17^\circ$, and Davies and Gill (1960) also found that the right ascension is $339^\circ$, although they determined the declination as $-19^\circ$. Ellyett *et al.* (1961) list the mean radiant as $\alpha = 340^\circ$, $\delta = -19^\circ$. There are several distinct radiants listed in Table 4(*a*) in the vicinity of the main $\delta$-Aquarid radiant. It is not unlikely that some of these have contributed to the data used in previous determinations of the $\delta$-Aquarid radiant. For example, group $7\cdot3$, which is similar to the $\delta$-Aquarids, is quite active at the same time and the greater right ascension could well have led to a mean value of about $342^\circ$ for the two radiants combined.

It is more difficult to explain the discrepancy in the coordinates for the Geminid shower. The position for 1961 agrees well with that determined for 1960; the slight differences are consistent with the 95% confidence limits. Combining the data for the two years, we have

$$\alpha = 109\cdot8\pm0\cdot8+1\cdot1(\odot-260\cdot1)^\circ,$$
$$\delta = +30\cdot8\pm0\cdot5^\circ.$$

Weiss (1959*b*), however, has determined the radiant coordinates to be

$$\alpha = 113\cdot4+0\cdot9(\odot-260\cdot2)^\circ,$$
$$\delta = +31\cdot4^\circ,$$

and he is supported by Davidson (1956), and also Whipple and Hawkins (1959). The latter list the radiant as

$$\alpha = 113^\circ,$$
$$\delta = +32^\circ.$$

The radiant has also been well studied by Kascheyev, Lebedinets, and Lagoutin (1960), using a radar technique similar to that of Davies and Gill. With 298 Geminid meteors detected in 1959, they determined the radiant as

$$\alpha = 111\cdot6+0\cdot9(\odot-260\cdot0)^\circ,$$
$$\delta = +32\cdot3-0\cdot2(\odot-260\cdot0)^\circ.$$

Although the Adelaide survey found several radiants in the vicinity of the Geminid radiant, none are close enough to cause confusion. The determination of this radiant imposes quite a severe test on the analysis of radiant coordinates from the diffraction and Doppler data, as it is a northern shower that transits at an elevation of only about 23°. The radiant data, particularly the declination, are more subject to error than for a radiant which transits at a high elevation. There is also another factor that warrants attention. The response of the equipment falls off very rapidly with increasing declination north of $+15°$; consequently, if the radiant is spread over several degrees at radio magnitude $+6$, there will be significant selection in favour of the southernmost meteors. This will cause the delineated radiant to be south of the mean value determined by observations in the northern hemisphere, or even by a different equipment at Adelaide. For these meteors, however, there is no evidence that the radiant is spread, and, in fact, the results of this survey and of those of Weiss and of Bullough (1954) suggest that the Geminids emanate from a point radiant. This being so, the selection mentioned above cannot account for the differences in declination determined at various localities, and, unless the radiant position varies from year to year, the most probable explanation lies in observational error.

## X. The Streams of Low Inclination

Before the streams listed in Table 4 can be discussed separately, the possibility must be considered of a low-inclination stream being detected twice—once before perihelion as a night-time shower, and again after perihelion as a day-time shower. The June day-time $\beta$-Taurids and the October night-time Southern Taurids are a famous case in point. It is now generally believed that the day-time Arietids and the Southern $\delta$-Aquarids are also associated in this manner, in spite of the relatively high inclination of the streams. This particular pair is discussed more fully later in this section.

Let us briefly review the factors that must be satisfied before classifying two showers as belonging to the same stream.

### (a) *Necessary Conditions for Double Intersection*

The orbits must be of similar size, shape, and inclination, but unless the inclination is zero they cannot be expected to be identical, as double intersection depends on the finite width of the stream. The perpendicular distance from the ecliptic plane to any point in an orbit has been given by Porter (1952) as

$$d = r \, . \, \sin i \, . \, \sin(\omega+\nu), \tag{23}$$

where $r$ is the distance from the Sun to the meteor, $\omega$ is the argument of perihelion, and $\nu$ the true anomaly. For orbits inclined at less than 30° to the ecliptic the night-time approach distance of a day-time stream, which intersects the Earth's orbit after perihelion with a true anomaly of $\nu_S°$, can be approximated by

$$d = \sin i \, . \, \sin 2\nu_S \qquad \text{a.u.} \tag{24}$$

The width of a stream must be greater than the distance given by (24) before a night-time shower can possibly be associated with a day-time one. Unfortunately, we have no direct means of measuring the width of a stream. The duration of a shower determines a minimum width, but the true width could be several times greater than this measure. For the day-time Arietids $d = 0 \cdot 45$ a.u., which is identical with the known minimum width of the δ-Aquarid stream (duration 26 days). Thus the relatively high inclination of 33° does not rule out the association of the two showers.

If a night-time shower is associated with a day-time one, the true anomaly of the night-time stream at detection should be given by

$$\nu_{as} = 360 - \nu_s{}^\circ, \tag{25}$$

where, as in (24), $\nu_s$ is the true anomaly of the day-time stream. Also, if the Earth's orbit is assumed to be circular, the arc of the Earth's orbit between intersections will be given by

$$360 - 2\nu_s{}^\circ.$$

Thus, if the solar longitude at the time of detection of the day-time shower is $\odot_s$, the solar longitude for the night-time shower, $\odot_{as}$, should be given by

$$\odot_{as} = \odot_s - 2\nu_s + 360^\circ. \tag{26}$$

The day-time showers listed in Table 4 were tested for night-time counterparts with the aid of (25) and (26). It was assumed that in most cases the errors in the mean orbits would be greater than the real differences to be expected from the finite width of the stream. This may not be so where the data are well defined, as for example, the S. δ-Aquarid stream. To allow for this doubtful assumption, the estimates of the standard deviations of the orbital elements given by the comparison data (Section VI) were doubled, as they were for the distinctness tests discussed in Section VII($d$). The mean orbits were then compared at the 5% significance level using a Student's $t$ analysis. Many possible pairs were listed, but the majority were excluded by the lack of agreement of $\odot_{as}$ with the value predicted by (26). It is difficult to lay down limits for this test, as the stream widths are not known, but a discrepancy of more than 30° in $\odot_{as}$ was deemed sufficient to rule out any association. The pairs of orbits finally accepted as possibly belonging to single streams are illustrated in Figures 10–19 and discussed in detail later in this section. Before turning our attention to these, however, let us briefly discuss the general activity of the day-time showers in May and June.

### (b) *The Day-time Showers in May and June*

In Section VII($c$) we considered some of the prominent peaks in the monthly distributions of meteors with apparent ecliptic longitude relative to the Apex of the Earth's Way. It was found that the extra activity from the vicinity of the Sun in May was due entirely to shower meteors, and most of the meteors giving rise to the very marked anti-Sun component from July to October were also members of streams. If the orbits of the two sets of meteors are examined, considering only those meteors which contribute to groups containing five or more orbits, a similarity is immediately noticed. The bulk of the Sun orbits in May are inclined less than 20° to the ecliptic plane, and have eccentricities ranging from $0 \cdot 7$ to $1 \cdot 0$. The values of $1/a$ extend from $0 \cdot 2$ to $0 \cdot 8$, but the majority lie between $0 \cdot 4$ and $0 \cdot 7$ a.u.$^{-1}$. Forty of the original

69 shower orbits in May have a value of true anomaly between 110° and 135°, which corresponds to a period of between 13 and 20 weeks before the Earth should again intersect these orbits, i.e. the intersection should occur between August and mid October.

An analysis of the anti-Sun component of the shower orbits over the period August to mid-October confirms that a large proportion of orbits have similar values of inclination, eccentricity, and semimajor axis to the May Sun group. From a total of 235 shower orbits, 84 satisfied the conditions

$$\begin{gathered} i < 20^\circ, \\ 0\cdot 7 < e < 1\cdot 0, \\ 0\cdot 4 < 1/a < 0\cdot 8, \\ 225^\circ < \nu < 250^\circ. \end{gathered} \tag{27}$$

Thus we have shown that the May Sun group of orbits and a large part of the August to October anti-Sun group are due to an extended complex of low inclination streams with aphelia between Mars and Jupiter.

A more detailed examination given below shows that these streams appear as day-time radiants in Pisces, Aries, and Taurus in May and June, and night-time radiants in the same zodiacal constellations during September and October. The variations in radiant activity from year to year shown by this complex must be due to the uneven distribution of meteoroids along the streams. The $o$-Cetids, a May day-time stream delineated by Aspinall and Hawkins (1951) illustrate this point; the stream has not been detected in later years. The variations in radiant position shown by some of the showers in October (Lovell 1954) are also probably due to the uneven distribution of meteoroids within the streams.

### (c) *Detailed Discussion of Showers*

We shall now consider in detail the streams associated with more than one shower. They are discussed in chronological order based on the day-time appearance. The orbits from the Adelaide data and, where applicable, those listed by Whipple and Hawkins, are illustrated in Figures 10–19. The latter are shown by dashed curves. Where more than 10 meteors were used to define the orbit, the Adelaide orbit is drawn with a slightly broader line. All the orbits have been projected orthogonally onto the ecliptic plane.

The position of the mean node, and thus the longitude of perihelion, depends to a considerable extent on the equipment operating times during 1961. These are given in Figure 9, which illustrates the position of the Earth relative to the First Point of Aries, ♈, during the periods of observation.

1. *Ophiuchids, Scorpids, and Comet Lexell* 1770 I;
*Radiants* 60·12·5, 61·12·3, *and* 6·9—*Figure* 10

McKinley (1961) has listed a night-time radiant in Ophiuchus at 260°, −20° for June 20. No measure of velocity has been available to determine the orbit. Ellyett and Roth (1955) recorded three centres of activity in this vicinity during their survey in June 1953. Two were well defined at 263°, −21° and 270°, −13°, and one was poorly defined at 252°, −20°. We have found three radiants in this vicinity during the period June 13–19; 6·6, 6·9, and 6·10. The orbit of 6·9 is similar to that of a stream detected in December. The latter appears as a minor radiant in Scorpius and

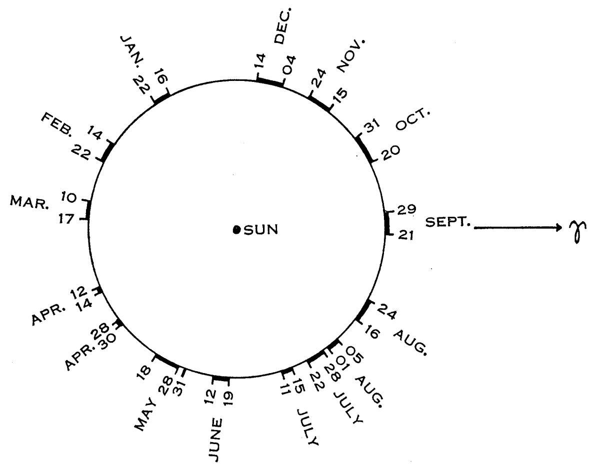


Fig. 9.—The times of observation during 1961, showing the positions of the Earth in its orbit relative to the First Point of Aries, ♈.

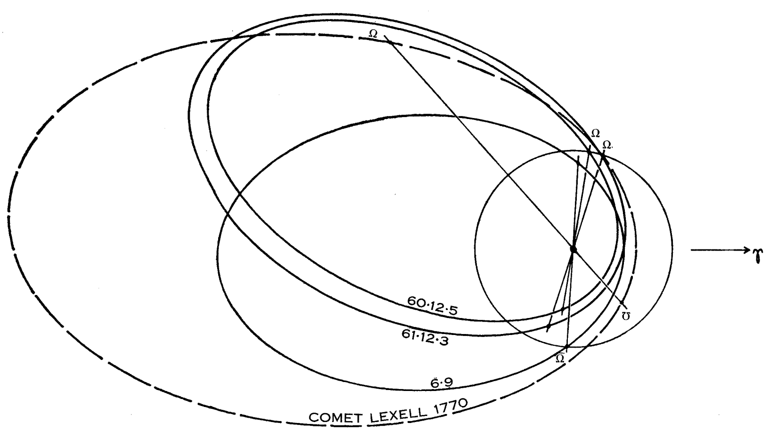


Fig. 10.—The orbits of the December Scorpids, 60·12·5 and 61·12·3, the June Ophiuchids, 6·9. ——— Adelaide data; – – – – Comet Lexell 1770 I (Porter 1952).

was observed both in 1960 and 1961. The two mean orbits, 60·12·5 and 61·12·3, agree quite well in view of the few meteors used in their delineation.

The association of the Scorpid shower with comet Lexell 1770 has been discussed elsewhere (Nilsson 1963); however, the author was not then aware of the minor June night-time radiant 6·9 in Ophiuchus. The agreement for the longitude of perihelion is much better for the meteor stream determined by this radiant and the comet than for the Scorpid orbit. However, it can be seen from Figure 10 that the observed node for the Scorpid meteors agrees perfectly with the date of closest approach of the cometary orbit, whereas the observed node of the Ophiuchid stream is about 2 weeks early. Porter has predicted radiants at 272°, −21° on July 5 and 256°, −25° on December 5 for any meteors travelling in the original orbit of comet Lexell, as compared to the mean radiants we have found, namely, 267°, −28° for June 16–17 and 247°, −25° for December 5–12. These discrepancies may indicate that the meteoric matter from comet Lexell has spread considerably and now forms a wide and diffuse stream.

Only the ascending node of 61·12·3 is significant, the observed node of the Ophiuchid stream 6·9 could in fact be descending, not ascending.

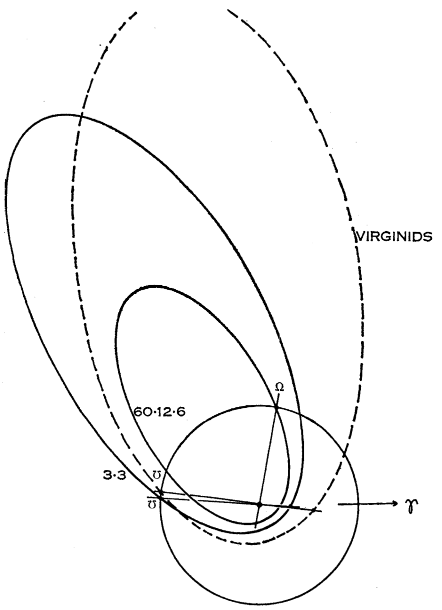


Fig. 11.—The orbits of the Virginid stream, detected in March (3·3) and possibly in December (60·12·6). ——— Adelaide data; – – – – Whipple and Hawkins (1959).

2. *The Virginid Stream;*
*Radiants* 60·12·6 *and* 3·3—*Figure* 11

Although the agreement between the mean orbit of radiant 3·3 and that given by Whipple and Hawkins for the Virginid stream does not appear good, we have tentatively identified our radiant with this stream. The meteors detected at Adelaide coming from this vicinity are difficult to group—there appears to be more than one radiant active at the same time, but our data are not sufficient to adequately resolve them. Apart from the three meteors used to determine the radiant 3·3, others were observed in orbits more closely resembling that of Whipple and Hawkins. One in particular, number 28056, was based on poor data, but agrees remarkably well with one of Whipple's (1954) Virginid orbits, number 1934. Davies and Gill also detected one Virginid meteor in 1955, number 2537, in an orbit which is similar to that of the photographic meteors. The three orbits are compared in Table 7 with the mean orbit of the group 3·3.

The radiant $3 \cdot 3$, which we have delineated, is further south than the other radiants and the geocentric velocity is higher—a mean of $32 \cdot 8 \pm 2 \cdot 0$ km/s, compared with about 28–29 km/s for a few meteors, such as number 28056.

The December radiant $60 \cdot 12 \cdot 6$ is listed as a possible night-time appearance of the same stream. This, too, is only poorly defined by three meteors, so that the statistical limits of error for both mean orbits are relatively large. Thus an association of the two is possible, in spite of the poor apparent agreement illustrated in Figure 11.

Table 7

Virginid orbits at various magnitudes

| Number | $\alpha$ | $\delta$ | $V_h$ | $a$ | $e$ | $i$ | $\omega$ | $\Omega$ | $\pi$ | $q$ | $M_r$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2537 | 186 | +6 | 39·4 | 3·8 | 0·87 | 8 | 274 | 1 | 274 | 0·50 | +8 |
| 28056 | 185 | +3 | 37·6 | 2·4 | 0·84 | 5 | 290 | 353 | 284 | 0·38 | +6 |
| 3·3 | 189 | −4 | 37·6 | 2·4 | 0·89 | 3 | 304 | 354 | 299 | 0·27 | +6 |
| 1934 | 190 | +3 | 37·8 | 2·5 | 0·85 | 6 | 290 | 357 | 287 | 0·38 | 0 |

If the stream lies in the orbit given by Whipple and Hawkins, we might expect to detect it again in October as a day-time radiant, but there is no sign of this in the Adelaide data.

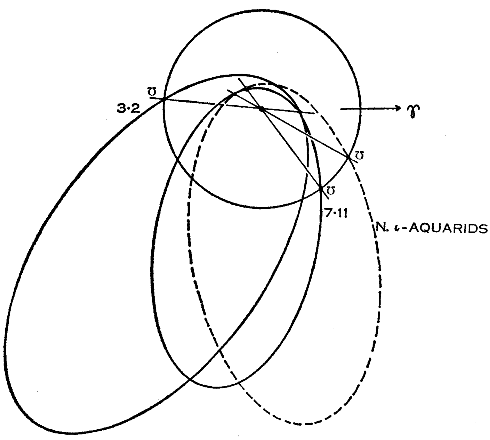


Fig. 12.—The orbits of the Northern ι-Aquarid stream, detected in March (3·2) and possibly in July (7·11). ——— Adelaide data; – – – – Whipple and Hawkins (1959).

3. *The Northern ι-Aquarid Stream;*
*Radiants* 3·2 *and* 7·11—*Figure* 12

The orbits of 3·2 and 7·11 are both poorly defined, and the radiant scatter of 7·11 is considerable; however, the latter has been tentatively identified with the N. ι-Aquarid stream. Whipple and Hawkins list the longitude of the ascending node for this stream as 151°, but this does not correspond to the listed date of peak activity, July 31. It corresponds instead to the latest date of detection, August 25. This discrepancy is obvious in Figure 12. The meteors at Adelaide were detected between July 25 and August 3.

Whipple and Hawkins give the extreme duration of the shower as 40 days, so it is quite possible that the minor radiant 3·2 in March represents the day-time return of this stream. The fact that both orbits are observed at a descending node would appear to contradict the association, but in neither case is the sign of the heliocentric latitude significant, so that in fact either node could be ascending.

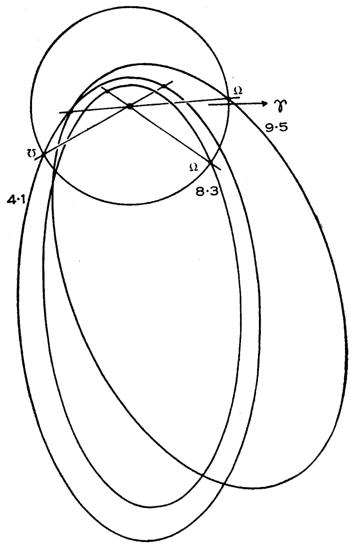


Fig. 13.—The orbits of three previously unknown shower radiants in April (4·1), August (8·3), and September (9·5).

4. *Radiants* 4·1, 8·3, *and* 9·5—*Figure* 13

The night-time radiant 9·5 is the best defined of these three. Although the differences between orbits 8·3 and 9·5 are too great to consider them as one, the day-time radiant 4·1 could be associated with either one. None of these radiants correspond to any well-known streams.

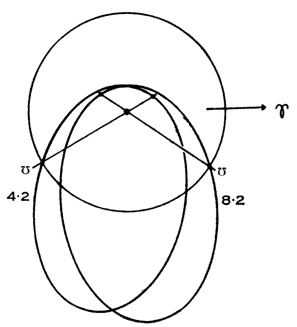


Fig. 14.—The orbits of two previously unknown shower radiants in April (4·2) and August (8·2).

5. *Radiants* 4·2 *and* 8·2—*Figure* 14

But for the apparent agreement with the better defined night-time radiant 8·2 in August, the April day-time radiant 4·2 would not qualify as a group. The scatter in the values obtained for the right ascension is excessive. The orbit is noteworthy in that its period is slightly less than that of the Geminid stream. The observed node of 4·2 is probably ascending, not descending, as the sign of the mean heliocentric latitude was not significant.

6. *ζ-Perseids, Piscids, and Southern Arietids;*

*Radiants* 5·1, 6·3, 9·1, *and* 10·1—*Figure* 15(*a*)

These groups of orbits are well defined and raise some interesting points. There seems little doubt that the radiant 5·1, detected from May 19–27, is due to the ζ-Perseid stream, although Whipple and Hawkins have given the period of detection as June 1–16. The orbit of the June stream 6·3 agrees very well with that given by Whipple and Hawkins for the ζ-Perseids. Statistically there is little difference between the orbits 5·1 and 6·3, and it is most probable that had the equipment been operating continuously, only one stream would have been delineated.

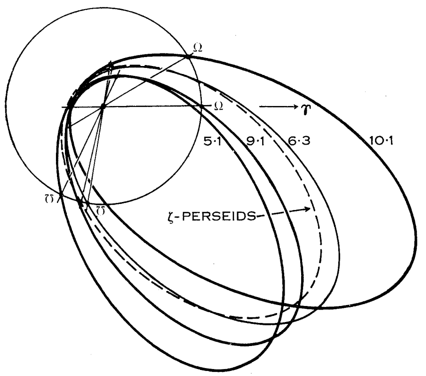


Fig. 15(*a*).—The orbits of the ζ-Perseids and October Southern Arietids. Orbits 5·1 and 6·3 are both from the ζ-Perseid stream; 9·1 is the orbit of a previously undetected September radiant in Pisces; 10·1 is the orbit of the S. Arietids. ———— Adelaide data; - - - - Whipple and Hawkins (1959).

The night-time radiant 9·1, active in Pisces throughout the interval September 22–29, is almost certainly due to the same stream. It is most interesting that this active radiant has not been previously recorded. September has been regarded as a month quite free of showers (e.g. Weiss 1957*b*), yet this survey has found it a most prolific month. Lovell (1954) concluded that the Southern Arietid stream incident upon the Earth in October, and accurately delineated by Wright and Whipple (1950), is probably closely associated with the ζ-Perseids. The S. Arietid radiant was detected during this survey, and the mean orbit, 10·1, is shown in Figure 15(*a*). It does not fit the predicted return of the ζ-Perseids nearly as well as the September Piscid orbit 9·1.

It is just possible that the two streams 9·1 and 10·1 are both part of a wide band of meteors, but consideration of the characteristics of the October Arietids and November Taurids does not encourage this view.

7. *Southern Arietid–Taurid Stream;*

*Radiants* 10·1 *and* 11·1—*Figure* 15(*b*)

Wright and Whipple (1950) analysed 102 meteors photographed at Harvard between 1896 and 1948 during the period October 15 to December 2. From their analysis they found two active radiants in Taurus, called the Northern and Southern Taurids, and two lesser centres of activity in Aries. These are similarly termed the Northern and Southern Arietids. There was some doubt, however, as to the distinction between the Southern Arietids in October and the Southern Taurids in November, and they combined the data into one moving radiant. Unfortunately, the Adelaide observations were not continuous over these 2 months, and hence the Adelaide data are not sufficient to determine whether or not the data should be combined. Statistically, the two mean orbits are significantly different, but if, as Wright and Whipple found, there is a steady change in the orbital elements with time, this difference is only to be expected in view of the times of observation.

If the two radiants are combined, the Adelaide radiant data agree quite well with the photographic observations: Wright and Whipple give the coordinates for the combined radiant as

$$\alpha = 53\cdot3+0\cdot7(\odot-223)^\circ,$$
$$\delta = +14\cdot1+0\cdot1(\odot-223)^\circ.$$

Combining the data for radiants 10·1 and 11·1 and correcting to $\odot = 223^\circ$, we find

$$\alpha = 50\cdot9+0\cdot6(\odot-223)\pm0\cdot6^\circ,$$
$$\delta = 14\cdot0+0\cdot2(\odot-223)\pm1\cdot0^\circ.$$

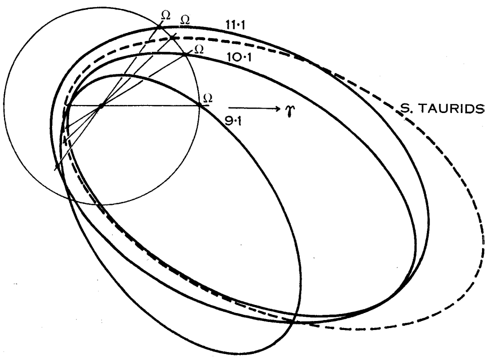


Fig. 15(*b*).—The orbits of the new September Piscids, 9·1, the October Southern Arietids, 10·1, and the November Southern Taurids, 11·1. ——— Adelaide data; – – – – Whipple and Hawkins (1959).

Despite the difference of 23° between the values of mean solar longitude observed for the two radiants during the Adelaide survey, the difference in longitude of perihelion $\pi$ is only a few degrees. The lack of variation of $\pi$ with time can be seen in Figure 15(*b*). It lends support to the hypothesis of a broad meteor stream extending from at least October 20 to November 23. The lack of any correlation of $\pi$ with time was noted by Wright and Whipple, although they did find systematic variations of the other orbital elements with time. The correlation of perihelion distance $q$ with solar longitude was most conspicuous. If we regard the mean orbits 10·1 and 11·1 in Figure 15(*b*) as defining the limits of a single broad stream, it can be seen that this variation should be most apparent. As the Earth moves across the stream, orbits of steadily increasing perihelion distance should be detected. Wright and Whipple determined the perihelion distance as

$$q = 0\cdot36+0\cdot008(\odot-223) \quad \text{a.u.}$$

We find, for a combined stream

$$q = 0\cdot39+0\cdot008(\odot-223) \quad \text{a.u.}$$

The combined Adelaide results also indicate a significant change in eccentricity and argument of perihelion with time. The combined mean orbit is given by

$$\begin{aligned} 1/a &= 0\cdot50\pm0\cdot02, \\ e &= 0\cdot81-0\cdot003(\odot-221\cdot3)\pm0\cdot01, \\ i &= 5\cdot6\pm0\cdot8^\circ, \\ \omega &= 111\cdot8-0\cdot83(\odot-221\cdot3)\pm1\cdot4^\circ. \end{aligned}$$

The decrease in geocentric velocity noted by Wright and Whipple is significant for our combined data, but is not quite as marked. We find

$$V_g = 27\cdot1-0\cdot20(\odot-221\cdot3)\pm0\cdot5 \text{ km/s},$$

compared to

$$V_g = 29\cdot5-0\cdot31(\odot-223) \text{ km/s}$$

for the photographic data.

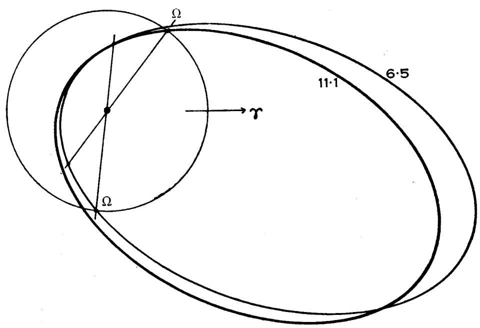


Fig. 15(*c*).—The orbits of the Southern Taurids, 11·1, and a June day-time radiant, 6·5.

It should be emphasized that the above correlations apply only to the combined data and, if the October Arietids and November Taurids are in fact separate streams, the correlations are without meaning. The fact that little or no correlation of the orbital elements with time was noted for either of the two showers treated separately, must be tentatively regarded as evidence against the hypothesis of a single stream. A continuous radio orbit survey over the period September–November should readily resolve this question. It would also determine what, if any, relationship the new September Piscid stream 9·1 bears to the known Arietid–Taurid stream(s). The difference in longitude of perihelion apparent in Figure 15(*b*) suggests that it is in fact quite separate.

8. *Southern Taurids* (*continued*);

*Radiants* 6·5 *and* 11·1—*Figure* 15(*c*)

There is excellent agreement between the June day-time stream 6·5 and the night-time Taurid stream in November. The June radiant was well defined by seven meteors detected during the period June 12–18. It is interesting to note that there is a significant correlation of radiant position with time, similar to that found for the Southern Taurid radiant, and that there is also a strong suggestion that the geocentric velocity varies even more markedly with time than was found for the combined Southern Arietid–Taurid stream. These facts strengthen the evidence that this June day-time radiant is due to the Taurid stream.

Elford (personal communication 1964), however, has re-analysed the data using the stream search program of Southworth and Hawkins (1963) and suggests that the May day-time shower 5·5 is due to the S. Taurid stream 11·1. There is certainly better agreement with regard to the argument of perihelion $\omega$ and the longitude of the node $\Omega$, but the eccentricity of the group 5·5 is slightly low. The sign of the mean heliocentric latitude of radiant 6·5 is not significant, so the node marked as ascending is quite possibly a descending node, for at least part of the stream.

The S. Taurid stream is of such dimensions that it may well be responsible for either or both of these day-time streams.

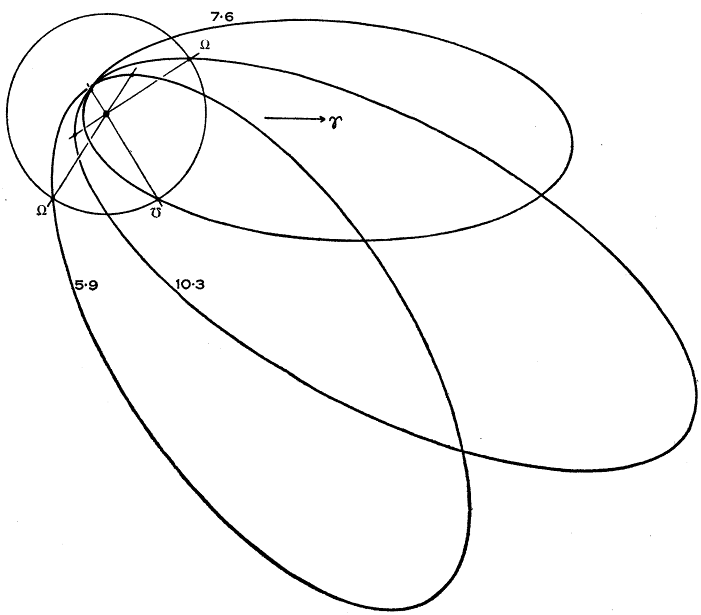


Fig. 16.—The orbits of three previously unknown shower radiants in May (5·9), July (7·6), and October (10·3).

The sign of the mean heliocentric latitude of radiant 6·5 is not significant, so the node marked as ascending is quite possibly a descending node, for at least part of the stream.

## 9. *Radiants* 5·9, 7·6, *and* 10·3—*Figure* 16

The night-time shower 10·3 could possibly be associated with either of the day-time showers 5·9 and 7·6. The values of orbital inclination suggest that radiants 5·9 and 10·3 are from the same stream, but both are observed with a significantly negative heliocentric latitude, indicating that both observed nodes are ascending. If this is so, the association is hardly possible. The difference in inclination between the streams 7·6 and 10·3 is slightly greater than that allowed at the 5% significance level, so this association is doubtful too. More data are needed to delineate the orbits of these streams more accurately.

10. *Southern δ-Aquarids and day-time Arietids;*

*Radiants* 6·1, 6·2, *and* 7·1—*Figure* 17

In spite of the seemingly close fit between the projected orbits 6·1 and 7·1 shown in Figure 17, the mean orbits of the two showers were not quite close enough to be classified as a single stream by the procedure discussed in Section X($a$). This is due to the difference in the values of inclination, $38\cdot9\pm1\cdot3°$ for 6·1 and $32\cdot5\pm1\cdot3°$ for the S. δ-Aquarid stream, 7·1.

The day-time Arietid orbit given by Whipple and Hawkins is also shown in Figure 17. They have listed the inclination of this stream as 21° and the inclination of the δ-Aquarid stream as 29·3°. The Adelaide survey resolved two separate day-time

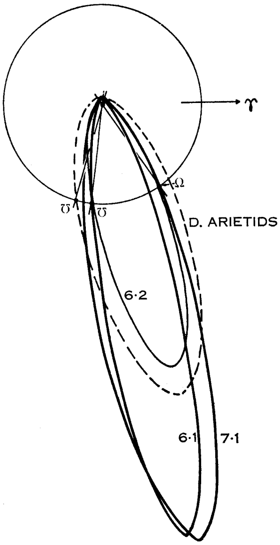


Fig. 17.—The orbits of the Southern δ-Aquarids, 7·1, and the day-time Arietids, 6·1 and 6·2. —— Adelaide data; – – – – Whipple and Hawkins (1959).

radiants in June with almost the same coordinates, 6·1 having a greater geocentric velocity than 6·2. It can be seen from Figure 17 that the mean orbit 6·2 is the one which best fits the day-time Arietid orbit given by Whipple and Hawkins. The coordinates of radiant 6·2 are

$$\alpha = 46\cdot1\pm1\cdot1°,$$
$$\delta = +26\cdot1\pm0\cdot8°,$$
$$V_{\mathrm{g}} = 38\cdot8\pm1\cdot1 \text{ km/s},$$

and for the day-time Arietids, Whipple and Hawkins give

$$\alpha = 44°,$$
$$\delta = +23°,$$
$$V_{\mathrm{g}} = 37\cdot4 \text{ km/s}.$$

However, we find that the mean inclination for this stream is $33 \cdot 4 \pm 1 \cdot 7°$, which is a long way removed from their value of 21°. For this particular radiant, the inclination of the corresponding orbit varies markedly with quite small changes in radiant coordinates. Also, the mean solar longitude for radiant 6·2 is 84·8°, whereas Whipple and Hawkins have given their data for $\odot = 76 \cdot 8°$. Lovell (1954) has observed that the inclination of this stream increases rapidly as the stream is crossed. For June 18, 2 days after the mean of the Adelaide observations, the Jodrell Bank survey found the inclination to be 34° in 1950 and 40° in 1951. These figures lend support to the mean value of inclination found by this survey; however, it should be noted that we found no significant correlation of inclination with time over the 3 days this radiant was detected.

In searching for the day-time radiant corresponding to the S. δ-Aquarid shower, we are thus left with the rather contradictory picture of radiant 6·1 agreeing well in so far as the size and shape of the orbit are concerned, but not with respect to the inclination, whereas the inclination found by the Adelaide survey for radiant 6·2 agrees well with that found for the δ-Aquarids, but the orbit is considerably smaller. As the width of the stream must exceed 0·45 a.u., it would not be surprising if branches of the stream exist in slightly varying orbits. If the meteoric matter is not uniformly distributed in these branches, different radiants of varying intensity will be apparent from year to year.

It would not be unexpected if the main radiant of this great stream showed a considerable diameter, due to the divergence of orbits within the stream. Weiss (1960*a*) was unable to measure the diameter of the S. δ-Aquarid radiant because the neighbouring minor showers could not be fully resolved. However, we have found (Section XII) the radiant diameter to be particularly small. After taking into account the correlation of radiant coordinates with time, the standard deviation of the radiant position is found to be $1 \cdot 7 \pm 0 \cdot 3°$. This deviation is within that expected from observational error alone.

### 11. *Sextanids and Geminids*; *Radiants* 9·2 *and* 12·1—*Figure* 18

The Sextanid stream 9·2 has been fully discussed in another paper (Nilsson 1963), but for completeness some of the major features of this stream are given here. It was first reported by Weiss (1960*b*), who observed it in 1957, but could not find any trace of activity in previous years, indicating that the shower is periodic in nature. The present author has established the orbital period as between 1·2 and 1·3 years, which is in agreement with the fact that the shower has only been observed on two occasions separated by 4 years.

The Sextanid orbit is very similar to that of the December Geminid shower, but the difference in the behaviour of the two showers appears to preclude any attempt to relate them to a single stream. The Geminids are noted for their remarkably consistent echo rate from year to year, in marked contrast to the periodicity of the Sextanids. The known minimum width of the Geminid stream is only 0·11 a.u.; it would have to be at least 0·34 a.u. if the same stream were responsible for both showers.

Although the Sextanids may not be due to the same stream as the Geminids, the orbits of the two streams are close enough to consider the possibility that the origins of the two streams are linked in some manner. Further observations of the Sextanids should prove of great interest.

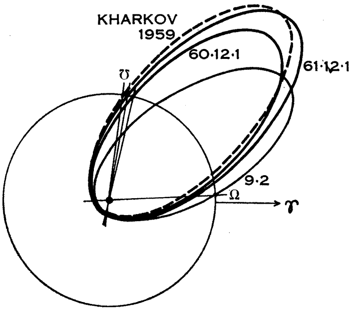


Fig. 18.—The orbits of the December Geminids, 60 · 12 · 1 and 61 · 12 · 1, and the September Sextanids, 9 · 2. ——— Adelaide data; – – – – Geminids, as observed at Kharkov in 1959 by Kascheyev, Lebedinets, and Lagoutin (1960).

## 12. *Radiants* 9 · 4 *and* 61 · 12 · 2—*Figure* 19

These two radiants are almost certainly from the one stream, as it is most unlikely that two such unusual streams would occur so close together with the same inclination. From the data in Table 4(*b*) it can be seen that the stream inclination is

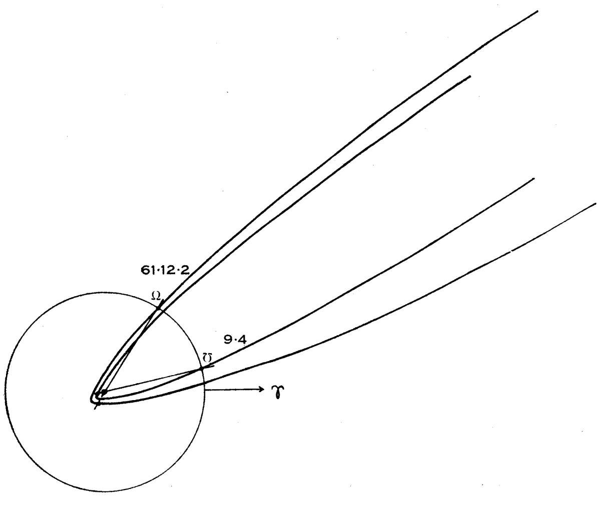


Fig. 19.—The orbits of two previously unknown shower radiants in September (9 · 4) and December (61 · 12 · 2).

about 22°, thus to intersect the Earth's orbit twice the stream must be at least 0 · 35 a.u. wide. The minimum width based on the observed duration of the two radiants, 9 · 4 (6 days) and 61 · 12 · 2 (5 days) is only 0 · 11 a.u. Thus we have evidence, if needed, that a stream can be at least three times as wide as indicated by the observed duration. The December radiant was also observed in 1960 (60 · 12 · 9).

## XI. Streams of Various Inclinations

The previous section was confined to a discussion of those streams listed in Table 4 which possibly give rise to two showers. In this section we shall discuss some of the other streams which are of particular interest.

### (a) *Deep Southern Radiants*

One aspect of particular interest to this survey is the determination of orbits for several showers not visible in the northern hemisphere. Some of these showers have been previously delineated by radiant surveys in the southern hemisphere, but no measure of the geocentric velocity of the meteors has been made, and consequently the orbits have not been determined. In this section we shall consider the radiants listed in Table 4(*a*) for which $\delta < -20°$.

1. *Ophiuchids and Scorpids*;
*Radiants* 60·12·5, 6·9, *and* 61·12·3—*Figure* 10

These showers and their relationship to the comet Lexell 1770 I have been discussed in the previous section.

2. *Puppids*;
*Radiants* 60·12·8 *and* 61·12·6

Ellyett and Roth (1955) found a weak night-time radiant at 114°, −25°, and later Weiss (1957*b*) reported a weak shower radiant at 124°, −36°, which he presumed to be the same. Later Weiss (1960*b*) determined these coordinates as 140°, −50°, which correspond well to the two determinations made during this survey. In 1960 four meteors were detected with a mean radiant at 138°, −53°, and in 1961 three meteors gave the position of this radiant as 143°, −54°.

As the inclination of this stream is 70°, no useful purpose is served by illustrating the orbit projected onto the ecliptic, as has been done for the streams of lower inclination. However, the low eccentricity of the orbit is noteworthy. This has been determined as $0·50 \pm 0·04$, which is lower than that of any other previously recorded stream. This fact, coupled with the high inclination, is interesting in view of the recent discovery of the low eccentricity "toroidal group" of sporadic meteors (Hawkins 1962). This group becomes more pronounced as fainter magnitudes are considered, in contrast to the ecliptic concentration of photographic meteors. The Puppids constitute the first stream with an orbit of the toroidal class to be observed.

3. *Radiant* 60·12·6—*Figure* 11

The poorly defined radiant 60·12·6 at 231°, −21° is probably the same radiant as Ellyett and Roth reported at 235°, −19°. In Section X we suggested that it might be due to the Virginid stream.

4. *Radiant* 60·12·7

This radiant at 155°, −61° has not been previously reported. Like the Puppids, it is a high inclination stream with an unusually low value of eccentricity, 0·69. The orbit is larger than that of the Puppids.

It is interesting that all the deep southern radiants discussed above are active in December.

### (*b*) *Other Radiants of Interest*

1. *Radiant* 9·10—*Figure* 20

The three meteors constituting this group were detected in September. The spread in radiant data is too great for the group to be definitely classed as a minor shower, however, in view of the unusual orbit illustrated in Figure 20, the possibility of such a stream existing is worth noting. The orbits are considerably smaller than those of the Geminid meteors, the latter mean orbit being shown for comparison.

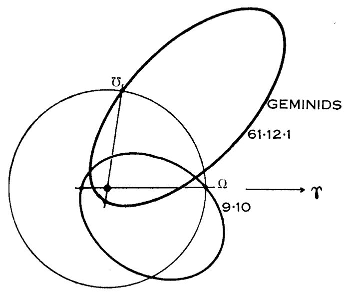


Fig. 20.—The orbit of a previously unknown minor stream in September (9·10), compared to the orbit of the Geminid stream (61·12·1).

It is possible that these three meteors have dispersed from a larger, more eccentric orbit populated by meteors of smaller surface area/mass ratio. The Poynting–Robertson effect (Robertson 1937) would cause the orbits of the smaller and less dense meteoroids to contract more quickly than the orbits of larger and more dense meteoroids. If this were so for radiant 9·10, we would expect the stream as we see it to be widely dispersed and to consist only of meteors of faint magnitudes. This would account for the lack of confirmation of the group in the photographic data of McCrosky and Posen, while radiant dispersion coupled with low activity would render detection by radiant surveys such as that of Weiss (1960*b*) well-nigh impossible.

Table 8

The Orionid Stream

| Group | $\alpha$ | $\delta$ | $V_g$ | $a$ | $e$ | $i$ | $\omega$ | $\Omega$ | $\pi$ | $q$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\eta$-Aquarids | 336 | + 0 | 63·0 | 5·0 | 0·91 | 160·0 | 83·0 | 43·1 | 126·1 | 0·47 |
| Orionids | 94 | +16 | 65·6 | 7·7 | 0·93 | 163·2 | 86·8 | 29·8 | 116·5 | 0·54 |
| Adelaide 10·2 | 97 | +14 | 64·7 | 6·3 | 0·92 | 160·3 | 90·9 | 32·3 | 123·2 | 0·50 |

2. *Orionids*;

*Radiant* 10·2

Six meteors were detected during October 24–30 from a radiant at 97°, +14°. The high geocentric velocity leaves no doubt that these were from the Orionid stream. The day-time $\eta$-Aquarid radiant which can be observed in early May is also due to this stream. Table 8 compares the orbital elements we have determined for the Orionid stream with those listed by Whipple and Hawkins for the Orionids and the $\eta$-Aquarids.

It can be seen that the values of the orbital elements for the Orionid stream determined at Adelaide are between those listed for the $\eta$-Aquarids and the Orionids, with the exception of the argument of perihelion, $\omega$.

3. *Monocerotids*;

*Radiant* 61·12·7

The data for this almost parabolic stream are given in Table 9. The radiant is weak, and the group was obtained by studying the December radiant data, rather than by the process discussed in Section VII. Whipple and Hawkins have listed the orbit as hyperbolic, but, although the Adelaide data include a few hyperbolic orbits, the mean eccentricity is less than 1·0. Both of the Monocerotid meteors detected in 1960 (not listed) had slightly lower geocentric velocities, about 39 km/s, and the two orbits were accordingly less eccentric than the mean orbit 61·12·7. However, statistically, no inference can be made from this fact.

TABLE 9

THE MONOCEROTID STREAM

| Group | $\alpha$ | $\delta$ | $V_g$ | $a$ | $e$ | $i$ | $\omega$ | $\Omega$ | $\pi$ | $q$ |
|---|---|---|---|---|---|---|---|---|---|---|
| W. and H. | 103 | + 8 | 42·6 | — | 1·002 | 35·2 | 128·2 | 81·6 | 209·8 | 0·19 |
| 61·12·7 | 102 | +10 | 42·2 | 5·6 | 0·98 | 39·0 | 138·9 | 76·2 | 215·1 | 0·11 |

Care must be taken not to confuse the separate and newly determined radiant at 95°, +15° (60·12·9 and 61·12·2) with the Monocerotid radiant at 102°, +10°. The values of geocentric velocity are similar, and the orbit of the former is also near parabolic; however, the inclination of the orbit is definitely smaller than that of the Monocerotid stream. The similarity of the orbits suggests that the two streams may be connected in some way.

4. *Southern $\iota$-Aquarids*;

*Radiant* 7·3—*Figure* 21

Whipple and Hawkins have listed a radiant at 338°, −14°, with a low level of activity enduring from July 16 to August 25. They give the mean value of $V_\infty$ as 35·8 km/s, which corresponds to $V_g = 34{\cdot}0$ km/s. We have detected a radiant at 346±2°, −19±1°, for which $\bar{V}_g = 33{\cdot}9 \pm 1$ km/s. This radiant was quite active throughout the period of observation, July 23 to August 4. The projection of the mean orbit, 7·3(1), is shown in Figure 21 together with the projection of the orbit listed by Whipple and Hawkins, S. $\iota$-Aquarids(1). In view of the argeement between the values obtained for the geocentric velocity, the large difference between the orbits seems inconsistent with the difference in mean radiant position. In an endeavour to account for this difference, the orbits were calculated from the mean radiants, as distinct from the normal procedure of calculating the means of the separate orbital elements. These results are given in Table 10, and illustrated in Figure 21. Orbit 7·3(2) has been calculated from the Adelaide radiant, and the S. ι-Aquarids(2) orbit has been calculated from the mean radiant listed by Whipple and Hawkins.

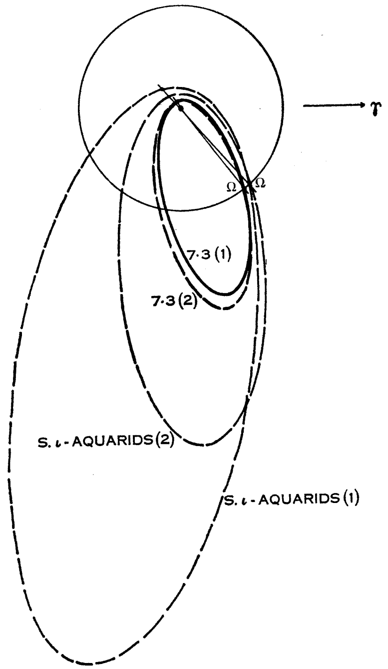


Fig. 21.—The orbits of the Southern ι-Aquarid stream, 7·3. ——— Adelaide data; – – – – Whipple and Hawkins (1959). (1) means of orbital elements; (2) orbits corresponding to mean radiants.

The two orbits calculated from the Adelaide data are essentially the same, but the two calculated from the data of Whipple and Hawkins are quite different. The internal consistency of the Adelaide data is thus much better. Furthermore, the orbit S. ι-Aquarids(2) is much closer to the Adelaide orbit than the orbit given by Whipple and Hawkins, which suggests that the Adelaide radiant may in fact belong to the same stream as they have listed as the S. ι-Aquarids.

Table 10

The S. ι-Aquarid Stream

| Group | $\alpha$ | $\delta$ | $V_g$ | $a$ | $e$ | $i$ | $\omega$ | $\Omega$ | $\pi$ | $q$ |
|---|---|---|---|---|---|---|---|---|---|---|
| W. and H.(1) | 338 | −14 | 34 | 2·9 | 0·92 | 6 | 128 | 311 | 79 | 0·23 |
| W. and H.(2) | | | | 1·7 | 0·91 | 9 | 141 | 311 | 92 | 0·15 |
| 7·3(1) | 346 | −19 | 34 | 1·1 | 0·90 | 36 | 154 | 306 | 100 | 0·11 |
| 7·3(2) | | | | 1·1 | 0·91 | 34 | 153 | 306 | 99 | 0·10 |

## XII. Radiant Diameter

Some measure of the radiant diameter at radio magnitude +6 can be obtained from the Adelaide data for the more intense streams. In Section VI, we found two independent estimates of the standard deviation of radiant position, due to observational error to be expected from a point radiant. These estimates were 2·0° and 3·3°, from the comparison data and the data variation study respectively. Table 11 gives the standard deviation of radiant position for those streams listed in Table 4 for which $n > 9$, $n$ being the number of meteors used to determine the radiant. The deviation $s$ has been calculated from

$$s^2 = \sigma^2(\alpha)+\sigma^2(\delta). \tag{28}$$

If we denote the standard error of the variance $s^2$ by

$$e = s^2(2/n)^{\frac{1}{2}}, \tag{29}$$

we can assume that the true value of $s^2$ lies within the range $s^2 \pm 2e$, with a confidence of approximately 95%. These limits of $s$, denoted by $s_{max.}$ and $s_{min.}$, are given in Table 11.

TABLE 11

STANDARD DEVIATIONS OF RADIANT POSITIONS

| Group | Name | $n$ | $s$ | $s_{max.}$ | $s_{min.}$ | $d$ |
|---|---|---|---|---|---|---|
| 60·12·1 | Geminids | 11 | 2·5° | 3·4° | 0·9° | — |
| 5·1 | ζ-Perseids | 18 | 3·6 | 4·7 | 2·1 | — |
| 5·2 | | 11 | 4·1 | 5·6 | 1·6 | — |
| 5·3 | | 10 | 2·9 | 4·0 | 0·9 | — |
| 5·6 | | 9 | 3·7 | 5·2 | 0·9 | — |
| 6·3 | ζ-Perseids | 9 | 4·3 | 6·0 | 1·0 | — |
| 7·1 | S. δ-Aquarids | 48 | 1·7 | 2·0 | 1·3 | — |
| 7·3 | S. ι-Aquarids? | 11 | 3·5 | 4·8 | 1·3 | — |
| 9·1 | | 19 | 3·7 | 4·7 | 2·2 | — |
| 9·2 | Sextanids | 9 | 2·6 | 3·7 | 0·6 | — |
| 10·1 | S. Arietids | 30 | 3·4 | 4·2 | 2·4 | 1·3° |
| 10·4 | | 10 | 5·1 | 7·0 | 1·7 | — |
| 11·1 | S. Taurids | 17 | 5·1 | 6·6 | 2·9 | 3·5 |
| 61·12·1 | Geminids | 11 | 1·7 | 2·3 | 0·6 | — |

The variance $s^2$ can be expressed as

$$s^2 = s_e^2+s_r^2, \tag{30}$$

where $s_e^2$ is the contribution to $s^2$ from all the observational errors and $s_r^2$ is the contribution from the real spread in the radiant position. If we assume $s_e$ to be the same for all radiants, the maximum value it may have can be no greater than the minimum value of $s_{max.}$ in Table 11. This is 2·0° for the S. δ-Aquarid radiant. However, as we have already mentioned in Section IX, the errors in radiant position are likely to be greatest for a northern radiant transiting low on the horizon. Thus the value of $s_{max.} = 2 \cdot 3°$ for the Geminid radiant can be taken as an upper limit for all $s_e$.

It follows that the minimum value $s_r$ can have for any particular radiant is given by

$$s^2_{r,min.} = s^2_{min.} - 2 \cdot 3^2, \tag{31}$$

and thus a minimum measure of the radiant "diameter" is

$$d = 2 \,.\, s_{r,min.}. \tag{32}$$

In only two cases is $s_{\text{min.}} > 2 \cdot 3°$, namely, the October S. Arietids and the November S. Taurids. The two values of minimum diameter for these radiants are $1 \cdot 3°$ and $3 \cdot 5°$ respectively. It is not possible from our data to give any figures for the other 11 radiants.

## XIII. Conclusion

We have shown that the combined c.w. and pulse technique of measuring individual meteor orbits can be successfully used to make a survey of the meteor streams incident upon the Earth. This method is particularly suitable for mapping the minor streams at radio magnitudes, as only a few orbits are needed to delineate a stream.

Marked improvements have been made possible in the field of data reduction by the use of digital computers, e.g. the accuracy of each orbit determination was improved considerably by making a least squares fit of the theoretical Fresnel diffraction waveform to all the turning points in the observed waveform for each echo, whereas in the past only two or three maxima or minima have been used to determine the velocity and relative time of arrival of the meteor at the specular reflection point.

A reasonable definition of a "shower" was devised and a digital computer was used to systematically search the data and isolate all the possible showers consistent with that definition. Such a definition does not overcome the basic difficulty of resolving minor streams from the sporadic background, but it does at least give some quantitative meaning to statements of the kind "it is estimated that about 25% of the meteors are associated with showers". The shower criteria used in this survey were of the form independently used by Southworth and Hawkins; it should be noted, however, that our approach differed in that we assumed observational errors were the main contributing factor to the apparent dispersion in the majority of the streams detected, whereas Southworth and Hawkins related the orbital differences between meteors of a given stream to a model of actual dispersion in interplanetary space. The difference in approach is due to the much smaller observational errors for the 360 photographic meteors used in their survey.

Southworth and Hawkins concluded that approximately 30% of their meteors were associated with recognizable streams. McCrosky and Posen, at a slightly fainter mean magnitude of $+0 \cdot 7$, found that about 18% of 2500 meteors could be classified as members of showers. This figure is probably an underestimate, as their search for showers was not conducted on the same systematic basis as either that of Southworth and Hawkins or the survey presented in this paper. Our figure of 25% is probably larger than would have been found had the survey been carried out continuously through the year. During the latter half of 1961 the recording times were biased towards periods of known shower activity. Ellyett, Keay, Roth and Bennett, at fainter radio magnitudes, have not been able to give a definite figure for the proportion of shower meteors, as their method of radiant determination is not adequate to resolve many of the minor streams. However, they believe that the figure is considerably greater than the 3% given by Davies and Gill from a survey of the orbits of more than 2000 meteors of radio magnitude $+8$. It is probable that, had Davies and Gill analysed their data in a manner similar to that which we have used, their proportion of shower orbits would be greater.

From the information we now have at various magnitudes, we know that streams become more difficult to resolve from the sporadic background as the magnitudes considered become fainter, but there is as yet no clear evidence that the proportion of meteors that are basically associated in groups of orbits actually decreases. This view appears to be substantiated by the work of Eshleman and Gallagher (1962), who found evidence of considerable shower activity at magnitude $+15$. To state the problem a little differently, it is not clear whether the sporadic background consists only of unresolved streams, some of which have been widely dispersed, or whether it has partly or wholly evolved in some other manner. Direct orbital measurements of very faint meteors and micrometeoroids are necessary to provide an answer to this and other related questions concerning the distribution of meteoric dust in the solar system.

We have shown, within the statistical limits set by the accuracy of the data, that many of the streams of low inclination are probably intersecting the Earth's orbit both before and after perihelion passage round the Sun. For example, we have found a previously unlisted shower, the September Piscids, which is a much better night-time match for the $\zeta$-Perseid shower than the previously suggested Southern Arietids. In connection with the latter shower, we have noted that valuable data concerning the Southern Arietid–Southern Taurid stream(s) could be obtained if an orbital survey were made continuously over the period September–December. Indeed, one of the difficulties in matching day-time and night-time showers is the uncertainty in the mean node of a particular stream due to only observing over a limited period. A continuous orbital survey would overcome this difficulty and also provide useful information concerning the durations of many of these minor showers.

Some inferences have been drawn in the past concerning the relationship between stream widths and radiant dispersion, e.g. by Whipple and Hawkins (1959). It should be pointed out that the only measure we have of stream width is the duration of a shower, and this can only be properly used as a lower limit for the stream width. Unless a large enough number of showers are used to make the assumption statistically valid, it is incorrect to assume that the duration of a shower is a measure of its width. We have shown in Section X that the true width of a stream can be at least three times that indicated by the shower duration.

Besides giving new data on some of the major stream complexes, such as the S. $\delta$-Aquarid/day-time Arietid stream, we have determined the orbits of some streams which have only been previously known by their radiant positions. For example, a new shower in December, the Scorpids, has been found to correspond to the poorly determined Ophiuchid radiant in June. The orbit of this stream suggests an association with the lost comet Lexell 1770 I. One of the most significant discoveries is that the Puppid shower belongs to a special class of low eccentricity, high inclination orbits which are quite distinct from the usual stream orbits.

## XIV. Acknowledgments

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