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Radar Determination of Meteor Orbits

Gerald S. Hawkins
Boston University and Harvard College Observatory

The development of the study of meteor orbits is described from the single station to the multistation systems. Meteor orbits are divided into two classifications, major streams and minor streams plus sporadics. The orbits of the major streams are similar in their distribution to the orbits of short-period and long-period comets, but the second group exhibits different characteristics. More than 99% of sporadic meteors with mass greater than 10 mg are moving in direct orbits. This unidirectional rotation is an important property of the particles in interplanetary space. At fainter magnitudes the results of the Harvard Radio Meteor Project and other researchers reveal an additional component. A large proportion of the smaller particles are moving in almost circular orbits tilted at a steep angle to the plane of the solar system. If this "toroidal group" represents a steady-state system then it is of considerable importance in cosmogony.

In the early days of radar astronomy the orbits of meteors were determined by the group method. The Fresnel oscillations in the amplitude of a meteor echo gave a measure of its velocity, and the mean of several hundred observations yielded the velocity of a meteor stream. The property of specular reflection enabled an observer to point his antenna towards a narrow band in the sky which was 90° from the radiant point of a meteor stream. When this band touched the antenna beam an enhancement in the echo rate was observed and the radiant point of the meteor stream could be determined. This method, and modifications of it, have been used successfuly by Hey and Steward (1947), by McKinley and Millman (1949), and by Aspinall, Clegg, and Hawkins (1951). The statistical approach of the group method proved its value in the systematic study of the nighttime and daytime streams (Lovell 1954) in both the northern and the southern hemispheres (Weiss 1955).

The group method for the determination of a meteor orbit is best suited, of course, to a well-defined meteor stream. Hawkins (1956a), however, found it possible to extend the method to a study of the radiant distribution of minor streams and sporadic meteors. In the absence of definitive data it is convenient to classify minor streams with sporadics at this juncture. By observing continuously for a two-year period, the radiant points were found to exhibit a symmetry with respect to the direction of motion of the earth in its orbit. Three stable concentrations of radiant points were found, one at the apex and two at an elongation of 65° on the ecliptic, close to the direction of the sun and antihelion point. The apex concentration was produced by meteor particles continually being swept up by the passage of the earth around its orbit. The other concentrations were due to sporadic meteors in a rosette of elliptical orbits of similar shape with directly moving particles. It is extremely difficult to correct the observed distribution of radiants to determine the heliocentric distribution—the number of particles that would be observed from a given direction if the earth were stationary and of zero mass. By assuming an average heliocentric velocity of 40 km/sec Fig. 1 was obtained. The radius vector represents the number of meteor particles per unit angle that intersect the earth's orbit at a given polar angle measured from the apex. It was impossible to distinguish between orbits of different inclinations, and the diagram is therefore a composite plot of all inclinations from 0° to 90°. Nor was it possible to correct for the selection factors of the radio method which had a strong bias against the weakly ionizing slow meteors, and the diagram is therefore drawn for a given limiting radio magnitude. The minimum detectable line density in the trail was 10^{10} electrons/meter. This early result gave an indication of the great preponderance of meteors in space which were moving in direct orbits.

A similar analysis of visual observations was made by Hawkins and Prentice (1957), where simultaneous

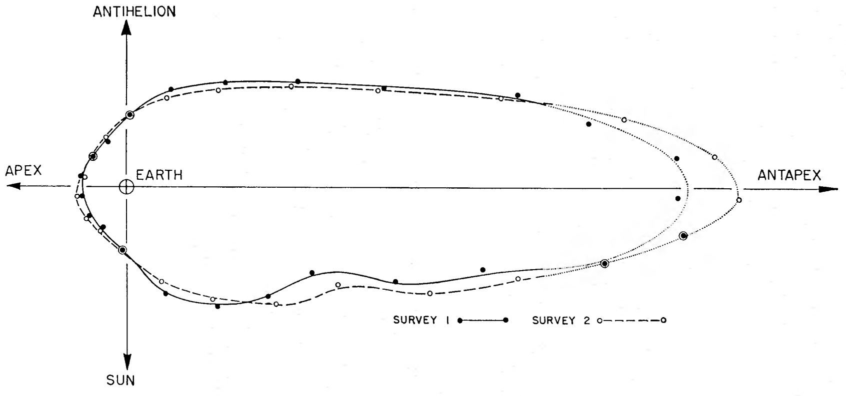

Fig. 1. Heliocentric distribution of orbital directions for meteors of constant radio magnitude.

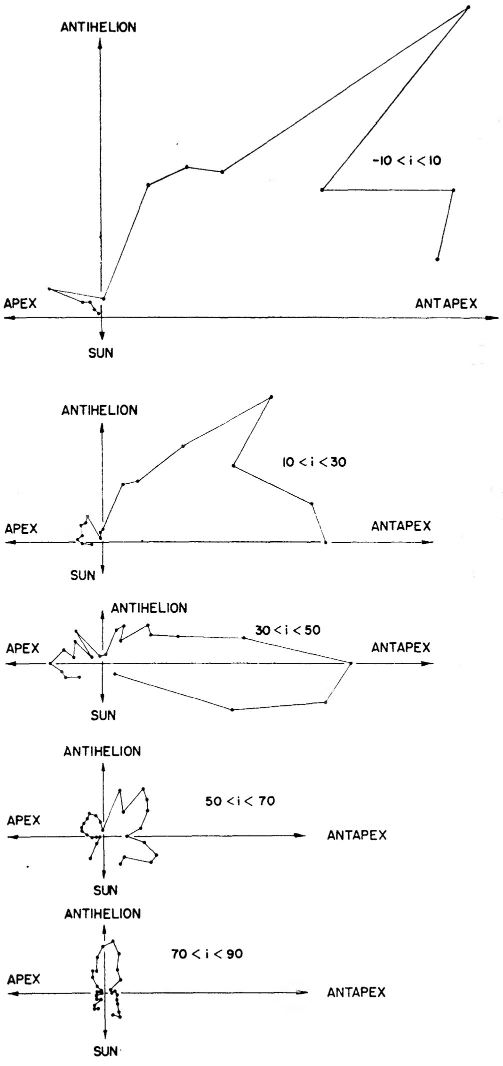

FIG. 2. Heliocentric distribution of orbital directions for meteors of constant visual magnitude.

observations were made from two spaced stations. By assuming a heliocentric velocity of 42 km/sec the heliocentric direction diagram could again be found as shown in Fig. 2. The results are quoted for a constant limiting magnitude of +4. For these observations it was possible to group the data according to the inclination of the orbit. The great preponderance of directly moving orbits was confirmed especially for the low-inclination orbits.

A recent theoretical investigation (Lazarus and Hawkins 1962) showed that the maximum ionization, $q_{\max}$ electrons/cm, produced by a meteor of mass m is given by the relation

$$q_{\max}=3.0\times 10^{-7}\, mv^3 (\text{cgs units}), \tag{1}$$

where v is the velocity of the meteor in the atmosphere in centimeters per second. The relation between mass and electron line density depends upon the probability β that an evaporated meteor atom will produce one electron. Jodrell Bank workers prefer an early value derived by Kaiser (1953) where β is almost independent of velocity. Whipple (1955), on the other hand, deduced from a comparison of the photographic and radar velocity distributions that $\beta\sim v^{3.9}$, and Hawkins (1956) found that the ionization of bright Perseid and Geminid meteors indicated $\beta\sim v^{4.6}$. The theoretical work of Lazarus shows that there is a threshold of 7 km/sec below which no ionization occurs and above which $\beta\sim v^{3.3}$. Equation (1) corresponds to $\beta\sim v^3$ if the luminous efficiency τ is constant, and $\beta\sim v^4$ if $\tau\sim v$. From the foregoing discussion it can be seen that there is an uncertainty in the exponent of (1) of approximately ± 1. The number of meteors has been found to increase as the mass of the meteoroid decreases (Hawkins and Upton 1958) according to the relation

$$n=6.36\times 10^{-17}\times m^{-1.34}, \tag{2}$$

where n is the number of meteors falling per cm^2 per sec with mass greater than or equal to m grams. It is now possible to make tentative correction for the variation of sensitivity and obtain the heliocentric distribution of meteors for constant limiting mass. The limiting mass for a meteor of velocity 70 km/sec with $q_{\max}=10^{10}$ electrons/m is 10 mg. Allowance must also be made for the variation of the capture cross section of the earth with meteor velocity (Schiaparelli 1871), and the probability of colliding with meteor particles in an orbit with inclination i which cross the earth's orbit at an elongation of θ from the apex. The rate of detection $n_{i\theta}$ from an isotropic distribution of orbits in space is given by the expression (Hawkins 1952)

$$n_{i\theta}=\sigma/(1-\cos^2\theta\cos^2 i)^{\frac{1}{2}}, \tag{3}$$

where σ is the capture cross section of the earth. The assumed heliocentric velocity was adjusted to a value of 36 km/sec. The combination of Eqs. (1), (2), and (3) is equivalent to a cosmic weight for radio meteors. Applying these corrections the ratio direct to retrograde orbits is found to be 1000. In other words, if we observed to a given limiting mass, more than 99.9% of the particles would be in directly moving orbits.

A check on this surprisingly high value can be obtained from the visual data. If we assume the luminous efficiency to be independent of velocity, then the intensity of the meteor at maximum brightness is proportional to mv^3 (Hawkins and Southworth 1958). The numbers in the observed direction diagram must therefore be scaled by a factor proportional to $v^{-4.02}$. Corrections must also be applied for the variation of the capture cross section of the earth with meteor velocity and for the probability of collision.

The ratio of direct to retrograde orbits is shown as a function of inclination in Fig. 3. This ratio increases from a value of unity at an inclination of 90° to 700 at an inclination of 0° and there is confirmation of the radio data. Although there is uncertainty in the value of the ratio, it does not affect the conclusion that most meteors in space partake of the general rotation of the solar system; the percentage of direct particles is either 99.0% or 99.9%.

To obtain more data on the minor streams and sporadic meteors it was necessary to study individual orbits. McKinley and Millman (1949) developed a three-station ranging method which gave orbital parameters for the few meteors which produced head echoes. Kaiser suggested a three-station system which gave meteor velocity by Fresnel measurements and direction cosines of the trail from the time delays between stations. This method was successfully used by the Jodrell Bank group (Davies and Gill 1960) and Kashcheyev *et al.* (1960) in the northern hemisphere, and Weiss (1961) in the southern hemisphere. An analysis of 2000 orbits for meteors to a limit of 7th mag. showed a surprising result. In addition to the preponderance of low inclination directly moving meteors there was a large group of orbits with eccentricities <0.3 and inclinations between 40° and 80°. This group was thought to be a population of small-sized particles moving almost perpendicularly to the plane of the solar system, though it was not possible to entirely discount the possibility of selection effects such as the poor observability of circular orbits with $i \sim 0°$ and the possibility of excessive deceleration in the atmosphere.

The Harvard Radio Meteor Project was set up to investigate the anomalous orbits and extend the observations to fainter radio meteors. The equipment consists of 6 spaced stations with a transmitter operating to 40 Mc and a peak power of 2 megawatts, and has been described in detail elsewhere (Hawkins 1962). Preliminary measurements to a limit of magnitude $+8$ have confirmed the results obtained at Jodrell Bank. At this limit the signals are several hundred times greater than noise and very clear Fresnel patterns are obtained. These patterns, together with a study of the distortions in the cornu spiral have permitted Southworth (1962) to carry out a careful analysis of deceleration. The radio meteors show approximately the same deceleration as meteors photographed with small cameras (magnitude -3) and conform to the classical theory (Whipple 1943). The typical radio meteor is either a single particle or a cluster of separate particles each conforming to the classical theory. The latter interpretation is probably the correct one because evidence of multiple reflection centers is given in the poor visibility of the Fresnel zones at the end of the trail. Thus it has been established

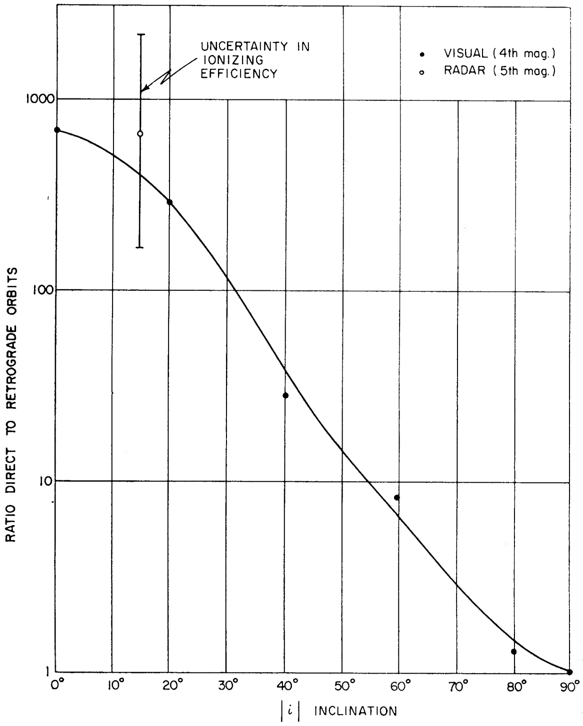

FIG. 3. Ratio of direct to retrograde orbits for meteors with a constant limiting mass of 10 mg.

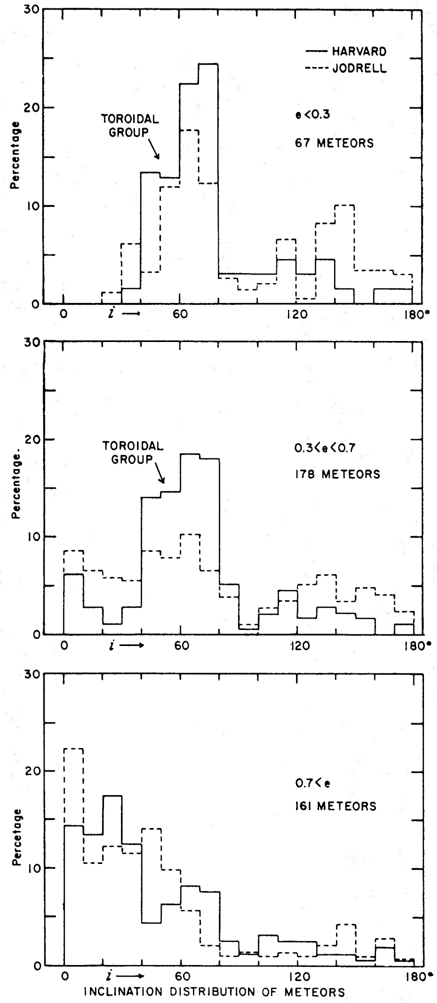

FIG. 4. Inclination distribution of the orbits of radio meteors.

that the measurements have not been unduly affected by excessive deceleration and the high-inclination orbits are indeed almost circular with $e<0.3$.

A comparison of the results obtained at Jodrell Bank with the results of the Harvard Radio Meteor Project are given in Fig. 4, where the percentage of orbits of various inclinations are shown for three ranges of ellipticity. The population of meteors moving almost perpendicularly to the plane of the solar system appears as the block in the diagram for $e<0.3$. At the Meteor Symposium at Harvard College Observatory and the Smithsonian Astrophysical Observatory in 1961 this population was called the *toroidal group* (Hawkins 1962). The orbits form a criss-cross pattern, and those which intersect the earth's orbit define a circular cylinder like the toroidal coil so familiar in the early days of "wireless telegraphy."

At the time of writing the Harvard Radio Meteor Project is capable of operating down to a magnitude of +11 and there are indications that the toroidal group becomes more dominant at the fainter magnitudes. There is also evidence to support the suggestion of smaller sized orbits for meteors of low mass. Thus radio meteor astronomy presents some new and awkward questions for the cosmogonist.

Why is the orbital distribution of sporadic meteors so different from that of the comets?

What segregation factors have virtually removed the retrograde particles?

How have the larger meteor particles become contained in a flattened disk?

How has the population of small-sized particles moving almost perpendicular to the solar system been produced?

These, and other questions, will probably be answered by the high-power radars now in operation in the United States, England, Russia, and Australia. To study the sporadic and minor stream complex we require systematic surveys extending over a period of at least two years with a rigid stabilization of sensitivity or sensitivity calibrations which will permit a correction for variations. A reduction rate approaching 1000 orbits per month is needed to obtain a significant measure of the statistics of meteor particles around the earth's orbit.

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