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NASA PROJECT APOLLO WORKING PAPER NO. 1096

MAJOR METEOROID STREAMS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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INTRODUCTION

The study of meteors is not a new science. Active work was begun over one hundred years ago after the appearance of the heavy Leonid meteor shower of 1833. The shower caused great excitement as thousands of meteor flashes were seen each minute in the skies over North America. There was a general decline in interest in the following years, only to be spurred by a huge Leonid meteor shower in 1866. Since then, meteor studies have been carried forward with the development of new and better techniques of obtaining information.

Meteor studies were conducted in the past in an effort to explain, in layman's terms, the mysteries of these intruders from interplanetary space. All this has changed with the advent of the space age, and now becomes one of vital importance in the design of space equipment. New study techniques involving radar, high speed photographic cameras, and satellites are employed in present meteor studies. Such a wealth of information has been obtained that a presentation of available meteor data would comprise many volumes. Therefore, it is the aim of this report to present data on a small, but very important aspect of the science of meteors. This data will concern the meteor streams now known which may exert an influence upon near-earth space exploration. It may also be stated that many of the numerical figures presented are average values and are, in the opinion of the author, the most reliable.

To more clearly present such data to the reader, a heliocentric scale model of the major meteoroid streams has been constructed and will be included in a brief discussion in this report.

DEFINITION

A meteor is a brief flash of light in the sky caused by the "burning up" of an object from space as it encounters the earth's atmosphere. The flash of light is caused by the extreme shearing and heating action of the atmosphere upon the high velocity particle. In order to clarify further discussion, the following definitions will be used:

1. Meteoroid - those particles pursuing elliptical to nearly parabolic orbits about the sun which may intersect the earth's orbit at a point. This term is applied to all such particles of small

diameter - about one meter and less. Larger bodies are called "Asteroids."

2. Meteor - the interaction of a meteoroid with the earth's atmosphere. This phenomena is seen from the earth as a streak of light appearing on the sky background.

3. Meteorite - the term denoting the residue of meteoroids striking the earth's surface. These particles must be large enough to survive atmospheric entry and impact. The smallest particles, 10^{-2} cm diameter or less, are often called micrometeorites. It may also be stated that meteoroids impinging upon the lunar surface are termed meteorites.

Two types of meteoroids are recognized at present: sporadic and stream. Sporadic meteoroids are solitary particles pursing independent orbits about the sun and having no known relation with any other particle. Their appearance as the familiar meteor flash is mostly random since they appear in any portion of the sky, at any time, and from any direction. At present, the sporadic meteoroid flux variation with visual magnitude and monthly flux rates are known from past observations. In contrast, stream meteoroid appearances may be predicted in advance with some reliability through the application of orbital mechanics. A stream consists of many particles in relatively close proximity to one another; each pursuing a similar but independent orbit about the sun. Since particles are usually scattered uniformly throughout the stream orbit, a predictable meteor influx is encountered each time the earth and stream orbit intersect. Several streams do not have uniformly dispersed particles but agglomerations instead. Meteor showers from such streams or swarms are irregular and produce large meteoroid influxes only when the nucleus of particles and the earth meet. The term "periodic" is used to denote this type of meteoroid stream; an example of this type is the Leonid and Giacobinid streams.

ORIGIN

There are four possible sources of meteoroid streams: (1) Interstellar material; (2) Lunar splash material; (3) Asteroids; and (4) Comets. A comparison of calculated velocities to the measured velocities of meteors may be used to determine their sources. Interstellar particles should have the highest velocities, that is, 72 km/sec or greater since the particles would be accelerated into the solar system from great distances by the sun. Cometary particles should possess the next highest velocities, 11 to 72 km/sec, depending upon whether the meteor is met head-on or merely catches up with the Earth. Particles of asteroidal origin should have velocities in the lower portion of the velocity range given for cometary bodies. Lunar splash material resulting from volcanic expulsion of material from the moon's surface or the result of meteoroid impingement should have velocities of 11 km/sec or less.

Present data show a meteor velocity range of 11 to 72 km/sec, corresponding to particles of cometary or asteroidal origin. About 1 percent of the data indicate interstellar or lunar material origins. However, this is less than the accuracy of measurements.

Current opinion favors the cometary origin hypothesis. Several comets have been shown to pursue orbits almost identical to those of some meteoroid streams. Table I lists several streams and the comets with which they may be associated. Particles of asteroidal origin seem to be limited to the sporadic meteoroid type, and are assumed to be sporadic in this report.

DATES OF STREAM APPEARANCES

About thirty major and four or five hundred minor meteor streams have been identified since the study of meteors began. Many streams have since disappeared and others have appeared for the first time. Today there are only twenty or thirty major streams. Table II, compiled from reference 1 and 2, is a listing of the present annual major streams and their periods of activity. The beginning and ending of the stream activity periods are ill defined. The dates of stream particle influx in Table II represent an influx equal to or greater than the sporadic background. The majority of streams show a slow increase in meteoroid influx from the starting date until maximum activity, and then the influx decreases rather rapidly. As a matter of interest, the dates of some minor meteor streams are also presented in Table III, references 1, 3 and 4.

INFLUX

Almost every stream is somewhat periodic in nature and has a variable particle influx. Average meteor rates for the major streams are given in Table II, column 4. These figures represent the average number of meteors from the stream of +5 magnitude or brighter that are visible to a single observer on a dark, clear night. Occasionally, a true periodic stream will increase the meteor rates ten to one hundred times normal. As for example the Leonids had 150,000 visible meteors per hour recorded in the past. Future dates of very high stream activity may be predicted with some success if past observations of the stream have been made. As an example, the Giacobinid stream was found to have a period of about 6.5 years. The last date of high particle influx from this stream was 1946. Therefore, high Giacobinid activity is indicated for the years 1952, 1959, 1966, and 1972. Similarly, the Leonid stream is expected to produce a larger than normal influx of particles about 1966.

Table IV presents the ratio of stream activity to the sporadic background influx and the number of days of maximum activity, reference 1. Table V lists the average sporadic flux per ft^2 per day, reference 5.

DENSITY

Stream meteoroids have a density range from 0.05 gm/cm^3 to 8 gm/cm^3, assuming sporadic meteoroids to represent degenerate streams, reference 6. However, particles at either extreme in density are undoubtedly rare. It is believed that larger particles possess smaller densities and resemble "dust balls", reference 7. These meteoroids must be very fragile and disintergrate rapidly upon atmospheric entry. Smaller particles have a higher density and at least approach that of stone. An average value of 0.5 gm/cm^3 is accepted for meteoroids of cometary origin which produce meteors of visual magnitude zero to 16. Meteors of asteroidal origin and magnitude zero or fainter are assigned a density of 3.5 gm/cm^3, reference 5.

MASS

The mass of a zero magnitude meteor of cometary origin is set at two grams, while a similar meteor of asteroidal origin has a mass of one gram. This corresponds to a density of 0.5 gm/cm^3 and 3.5 gm/cm^3 respectively. The mass of a meteoroid varies directly with its brightness, that is, an asteroidal meteor of +1 magnitude will have a mass of $\frac{1}{2.51}$ grams. Table V lists the absolute magnitude of meteors, their corresponding masses, and the influx rate of sporadic meteors. The mass-absolute magnitude relation should apply equally to stream meteors.

Radiation pressure sets a lower limit on the mass of a particle from a meteoroid stream. This limit is about 10^{-14} grams or +35 magnitude. Particles of greater mass are gradually swept into the sun due to the Poynting-Robertson effect. Since the smaller particles are removed more quickly by this effect, it is expected that the oldest streams are lacking in particles in this mass range. A stream such as the Perseids, which is possibly 10^4 years old, may have a lower limit on particle size of +25 magnitude or 10^{-10} grams. More recent streams will not have had sufficient time to lose particles from the stream, and the orbits of individual particles will merely appear more circular with decreasing particle size. Consequently, as the earth intercepts the meteoroid stream there is an apparent grading of particle size across the stream. In this manner, an influx of very small particles may precede or follow the main body of a stream. A search for this effect among the major streams has met with little success. Only the δ-Aquarid and Leonid streams at present indicate a possibility of such a particle separation.

RADIUS

Meteoroid diameters may be found in Table V. These figures are very sensitive to mass and density estimates, and in the past have shown quite a wide range of values for any particular magnitude particle. With the present value of 0.5 gm/cm^3 density and 2 grams mass for a zero magnitude cometary particle, the resultant particle radius is found to be 0.98 cm. Similarly, for an asteroidal particle of 3.5 gm/cm^3 density, 1 gram mass, and of zero magnitude, the radius is 0.41 cm.

Since particle radius is very important in meteoroid studies, a discussion of dispersive effects involving particle size in the streams would be of value. The Poynting-Robertson effect and radiation pressure are perhaps the most effective dispersive forces. The Poynting-Robertson effect (P-R) is a tangential drag produced upon a particle by the absorption and subsequent re-emission of sunlight by the particle. The amount of the effect is dependent upon particle radius, density and velocity. Over a cosmologically short period of time, the particle will spiral in toward the sun; vaporizing at a distance of about 0.1 A.U. from the sun. Since the P-R effect varies according to the length of time of exposure to the effect, a separation of particles from the body of the stream occurs due to the numerous stages of orbital disintegration for the various types of particles. The oldest streams, 10^4 years and older, will lack particles of the smallest sizes, about +25 magnitude and less.

Radiation pressure will have the opposite result of the P-R effect. Small particles experience a radial acceleration due to the action of sunlight pressure and are essentially "blown" out of the solar system. The largest particle affected by radiation pressure is given by $r\rho = 5.72 \times 10^{-5}$ gm/cm^2, where r = particle radius and ρ = density, reference 1. Due to radiation pressure, the P-R effect will be operative only on particles larger than the above limit. For meteoroids of density 3.5 gm/cm^3, the smallest particle remaining in a stream due to radiation pressure is 0.16μ. For cometary meteoroids, the smallest particle radius remaining is approximately 1.2μ.

VELOCITIES

Table II presents geocentric velocities of meteoroids from various streams when entering the Earth's atmosphere. The average stream meteor velocity is 30-35 km/sec. The velocity varies from 11 to 72 km/sec, depending upon whether the particle is met head-on or if it catches up with the Earth, reference 8. In the same manner a space vehicle could intercept these particles with velocities from nearly zero to about 81 km/sec. A determining factor of meteoroid velocities is the shape of the particle orbit. Streams exhibit orbital eccentricities from nearly circular to parabolic, with the majority possessing the more eccentric orbits. Since all particles of a stream move in essentially parallel orbits, it is sufficient to state that all particles of a particular stream move at approximately the same velocity when at the same distance from the sun. Meteoroids entering the Earth's atmosphere from local midnight to local noon will have higher velocities than during the remaining period of time. This is due to the addition of the forward velocity of the Earth in it's orbit to that of the meteoroid. Meteoroids entering the Earth's atmosphere after local noon and before midnight have to "catch up" with the Earth and, therefore, enter at lower velocities.

ORBITAL ELEMENTS

Six elements are needed to define an orbit. They are:

- a - the semi-major axis of the ellipse
- e - eccentricity of the orbit
- i - the inclination of the meteoroid orbital plane to that of the ecliptic plane
- Ω - the longitude of the ascending node
- ω - the latitude of perihelion
- T - the time of perihelion passage

The ascending node Ω is the point at which the meteoroid passes from the south to north side of the ecliptic and its longitude is measured from the vernal equinox γ in the plane and direction of the earth's orbital motion. This is shown in figure 1 as angle $\gamma s \Omega$. The latitude of perihelion ω is measured from the ascending node Ω along the orbit in the direction of motion of the particle to the perihelion point. The inclination (i) is the angle between the two planes measured counterclockwise from the meteoroid ascending node.

The size of the meteoroid orbit is thus defined by a, its shape by e, the orientation of its plane in space by i and Ω, and the direction of the major axis in that plane by ω. The position of the particle in the orbit is defined by the sixth element - T.

Additional parameters are often added to simplify the description of the orbit. The perihelion distance q is often used in the determination of the equation of motion. The longitude of perihelion $(\Omega + \omega)$ or π appears in old references and is now seldom used.

In order to demonstrate the use of an orbital equation, the following discussion may be helpful. The equation of an orbital ellipse may be conveniently expressed in polar coordinates using the defined elements of the orbit. The polar equation of an ellipse is represented by, reference 9,:

$$r = \frac{q\ (1 + e)}{1 + e \cos \theta} \tag{10.1}$$

r = radius vector
q = perihelion distance
e = eccentricity
θ = the position angle of the meteoroid in its orbit as measured in the direction of motion and from the perihelion point (q).

Substituting values for θ into the equation allows distance of the meteoroid from the sun to be determined. Table II contains the orbital elements of the major meteoroid streams. The accuracy of the orbital elements is low and represents elements of the major portion of each stream only. The orbital shape of the Geminid stream may be used as an example. From Table II, the following data for this stream may be found, q = 0.14 A.U. (Astronomical Units) and e = 0.89. Substituting values for θ into equation 10.1 until (r) results in a figure larger than 1.0 A.U. will enable the orbital shape of the stream to be determined.

For θ 0°	r = 0.1400
15°	= 0.142
30°	= 0.1494
45°	= 0.1624
60°	= 0.1831
90°	= 0.2646
120°	= 0.4768
150°	= 1.154
330°	= 0.1494

The orbit is shown in figure 2 as only an approximation to the orbital curve since the inclination of the two planes has been neglected. The orbital curves of the various streams may be found in a similar manner; some of these are shown in figure 3 as compiled from reference 1.

MAJOR METEOROID STREAM MODEL

To more clearly show the relation between major meteoroid streams and the earth, a heliocentric scale model as illustrated in figures 4 and 5, has been constructed. The model may be used to show approximate: (1) dates of meteoroid influx upon the Earth for each stream (2) shape of the stream orbits, (3) angle of particle influx, (4) direction of motion, et cetera. A two-foot circular piece of plexiglass was chosen to represent the orbital plane of the Earth. A thin scribe mark with a ten inch radius about the center traces the path of the Earth in its annual journey around the sun. On this scale, one inch equals 9.3 million miles. The reference position for astronomical measures, the Vernal Equinox, is indicated by a scribe mark between the sun and the March 22 position of the Earth in its orbit. In order to show the shape of each meteoroid stream orbit, it was necessary to determine the equation of the orbit in polar coordinates and draw to the scale of the model. Aluminum rods shaped to match the stream orbits are fastened to the plexiglass plane at the proper angles and positions. The angle of the stream rod is indicated by the inclination (i) of the stream orbit. It must be remembered that the inclination is measured at the ascending node of the stream and counterclockwise from the ecliptic plane to the stream plane. The correct position of the rod is determined by the date of particle influx. If the heliocentric longitude of the stream ascending node corresponds with the heliocentric longitude of earth on the date of stream activity, the stream rod is placed at this date on the plexiglass plane. Direction of particle influx is from south to north. If by the above description the heliocentric longitude of the stream ascending node (Ω) is 180° from the heliocentric longitude of the earth on the date of particle influx, stream particles will appear from the descending node of the stream. This indicates a direction of particle motion from north to south. The position to fasten the stream rod, in this case, is at the point on the earth's orbit equal to the heliocentric longitude of the stream descending node. Also, when attaching the stream rods, the perihelion point must be kept in the proper relation to the sun; this is determined by the latitude of perihelion (ω).

A white band on the ecliptic plane at the base of each stream rod indicates the length of time of stream activity. The length of the white areas, as shown in figure 5, denote dates on which activity is as great or greater than the background sporadic influx. In some cases, several streams overlap in activity dates and a single white area represents the total period of stream activity.

Only major streams have been shown on this model. Some are periodic and show low influx rates normally but have been included because of their potential importance. From January 4 to April 19, minor streams only are present and therefore not included on this model. This does not indicate a period of time lacking in meteoroid activity, but one with minimum particle concentrations.

CONCLUSIONS

The large amount of cometary and asteroidal data on meteoroid streams has been compiled into a form for meteoroid application that includes particle density, size, velocity, and orbital elements.

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APPENDIX A EXPLANATION TO THE TABLES OF RADIATION PRESSURE AND THE POYNTING-ROBERTSON EFFECT

The maximum particle size affected by radiation pressure for various particle densities is given in Table A.1. Values were calculated from the equation $r\rho = 5.72 \times 10^{-5}$ gm/cm^2, where r equals particle radius and ρ equals particle density. This equation is derived by equating the radial force of radiation pressure to the gravitational attraction by the sun on the particle. Since the force of gravitation and radiation pressure vary in the same manner with distance, the equation does not involve changes in particle distance in the solar system. The effect of the remaining important dispersive force; the Poynting-Robertson effect, is presented in Table A.2. The period of time necessary for a particle to spiral into the sun, particle lifetime, was calculated for each stream. The particle was chosen to be 2μ radius with a 0.5 gm/cm^3 density. Since the Poynting-Robertson effect varies inversely with particle radius and density, the lifetime of any other particle of a given stream, density and radius may be determined from this table and the equation:

$$\Delta t = \rho r t_s$$

where

Δt = lifetime of particle
ρ = particle density
r = particle radius, μ
t_s = lifetime of 2μ, 0.5ρ particle in the stream

The true radiant position of each stream expressed in heliocentric ecliptic coordinates is presented in Table A.3. Heliocentric ecliptic longitude of 0° is the position of the earth in its orbit at the autumnal equinox.

TABLE I*.- ORBITS OF SOME METEOR SHOWERS AND ASSOCIATED COMETS

Shower and Comet	ω (deg)	Ω (deg)	i (deg)	e	a (A.U.)	q (A.U.)	p (yr)	V Geocentric (km/sec)
Perseids	155	138	116	0.96	22.6	0.96	108	60.5
Comet 1862 III	153	138	114	0.96	24.7	0.96	122	----
Leonids	179	233	163	0.91	10.3	0.99	33	72.0
Comet 1866 I	171	231	163	0.91	10.3	0.98	33	----
Lyrids	213	30	80	1.0	----	0.90	---	48.6
Comet 1861 I	213	30	80	0.98	56.0	0.92	415	----
Andromedes	222	246	13	0.75	----	0.86	---	16.0
Biela's Comet, 1852 III	223	246	13	0.76	3.52	0.86	6.6	----
Eta Aquarids	100	45	162	0.97	----	0.60	---	60.0
Halleys Comet	112	57	162	0.97	17.9	0.59	76	----
Orionids	143	28	161	1.0	----	0.52	---	66.5
Draconids	175	196	31	0.71	3.52	1.00	6.6	23.3
Comet Giacobini-Zinner, 1946 V	172	196	31	0.72	3.64	1.00	6.96	----
Taurids	109	47	5	0.82	2.22	0.39	3.3	30.6
Encke's Comet	185	335	13	0.85	2.22	0.33	3.3	----
Ursids	206	271	54	0.84	----	0.94	---	33.4
Comet Tuttle I	207	270	55	0.82	5.73	1.02	13.7	----

ω = latitude of Perihelion
Ω = longitude of ascending node
i = orbital inclination
e = eccentricity of the orbit
a = semi-major axis
q = perihelion distance
p = period
V = Geocentric Velocity

*Watson, F. G., 1952, "Between the Planets, Reference 10.

TABLE II.- ORBITAL ELEMENTS FOR MAJOR METEOR STREAMS

Name	Period of Activity	Date Max.	Normal Activity per hour	Ω deg.	π deg.	ω deg.	ι deg.	ϵ	q a.u.	a a.u.	Velocity Geocentric Km/sec	Period Years
Quadrantids*	Jan. 2-4	Jan. 3	80	282	92	166	67	0.46	0.97	1.7	42	13
Lyrid	April 19-22	April 21	7-10	30.5	--	210	81	0.88	0.90	---	48	19.8
η-Aquarid	May 1-8	May 4-6	10-34	45	152	108	162	0.96	0.66	17.95	64	11
O-Cetid	May 14-23	May 14-23	20	238	89	211	34	0.91	0.11	1.3	37	1.5
Arietid	May 29-June 19	June 6	10-80	77	106	29	21	0.94	0.09	1.6	38	1.8
ζ-Perseids	June 1-16	June 6	30	78	--	59	4±2	0.79	0.35	1.6	29	2.2
β-Taurids	June 24-July 5	June 28	20	276	162±4	246±4	9±4	0.86	0.36	2.5	31	3.3
δ-Aquarid	July 26-Aug. 5	July 28	15	305	101±2	156±2	24±5	0.96	0.08	1.8	40	3.6
Perseid	July 15-Aug. 18	Aug. 10-14	50	142	--	155	114	0.96	0.97	23	60	109.5
Giacobinid*	Oct. 9-10	Oct. 10	200	196	--	172	30.8	0.72	0.99	3.5	23	6.57
Orionid	Oct. 15-25	Oct. 20-23	10-15	29.3	103	87.8	163	0.92	0.54	6.32	66	
Arietid, Southern	Oct.-Nov.	Nov. 5	8-15	27	150	122	6	0.85	0.30	1.91	28	2.64
Taurids, Northern	Oct. 26-Nov.22	Nov. 10	4	221	160	308	2.5	0.86	0.31	2.16	29	3.2
Taurids, Night	Nov.		10	220	160	300	3	0.86	0.3	2.1	37	3.3

*Periodic streams

TABLE II.- ORBITAL ELEMENTS FOR MAJOR METEOR STREAMS - Concluded

Name	Period of Activity	Date Max.	Normal Activity per hour	Ω deg.	π deg.	ω deg.	i deg.	ϵ	q a.u.	a a.u.	Velocity Geocentric Km/sec	Period Years
Taurids, Southern	Oct. 26-Nov. 22	Nov. 5	4-15	45	157	112	5.1	0.85	0.36	2.39	28	3.69
Leonid*	Nov. 15-20	Nov. 16-17	8-10	234	49	179	162	0.92	0.99	12.8	72	33.25
Bielids*	Nov. 15-Dec. 6		20-30	250	109	223	13	0.76	0.88	3.6	16	6.6
Geminid	Nov. 25-Dec. 17	Dec. 12-13	20-60	261	---	324	24	0.90	0.14	1.4	35	1.7
Ursids	Dec. 20-24	Dec. 22	10-40	270	---	210	56±3	1.0	0.92	--	37	

*Periodic streams

TABLE III.- MINOR METEOR STREAMS*

Name		Dates of Activity
κ	Cygnids	Jan. 17
α	Aurigids	Feb. 5 - 10
ζ	Bootids	Mar. 10 - 12
	Piscids	May 7 - 14
ν	Piscids	May 12 - 13
η	Pegasids	May 30
α	Scorpiids	June 2 - 17
54	Perseids	June 21 - July 9
i	Draconids	June 27 - 30
γ	Draconids	June - Sept.
α	Orionids	July 12 - 17
α	Capricornids	July 18 - 30
θ	Aurigids	Aug. 12 - Oct. 2
κ	Cygnids	Aug. 10 - 20
ο	Draconids	Aug. 21 - 23
ζ	Draconids	Aug. 21 - 31
ε	Perseids	Sept. 7 - 15
ε	Arietids	Oct. 9
	Draco	Oct. 12 - 23
ε	Taurids	Oct. 30 - Nov. 17

* Compiled from Meteor Astronomy, A. C. B. Lovell and Smithsonian Contribution to Astrophysics, Vol. 4, No. 3 and 4.

TABLE IV.- RATIO OF METEOR SHOWERS TO SPORADIC ACTIVITY

Name of Shower	Arietids and ζ-Perseids	β-Taurids	Quadrantids	Perseids	Geminid
Number of Days of Activity	16	11	2	9	6
Ratio $\frac{\text{Shower}}{\text{Sporadic}}$	3.9	0.7	10	2	7.2
Density in Orbit (kg/km^3)	6.0×10^{-12}	1.4×15^{-12}	15.1×10^{-12}	2.4×10^{-12}	12.0×10^{-12}

TABLE V.- SPORADIC COMETARY AND ASTEROIDAL METEOROID CHARACTERISTICS

Visual Magnitude	Velocity km/sec	Asteroidal			Cometary		
		Mass grams	Diameter μ	Flux Particles/ft^2-day	Mass grams	Diameter μ	Flux Part./Ft^2-day
0	28	1	8.17×10^3	4.24×10^{-11}	2	1.97×10^4	3.83×10^{-10}
1	28	3.98×10^{-1}	6.01×10^3	1.07×10^{-10}	7.96×10^{-1}	1.45×10^4	9.62×10^{-10}
2	28	1.58×10^{-1}	4.42×10^3	2.68×10^{-10}	3.17×10^{-1}	1.06×10^4	2.42×10^{-9}
3	28	6.31×10^{-2}	3.25×10^3	6.72×10^{-10}	1.26×10^{-1}	7.84×10^3	6.08×10^{-9}
4	28	2.51×10^{-2}	2.39×10^3	1.69×10^{-9}	5.02×10^{-2}	5.76×10^3	1.53×10^{-8}
5	28	1.00×10^{-2}	1.76×10^3	4.24×10^{-9}	2.00×10^{-2}	4.25×10^3	3.83×10^{-8}
6	28	3.98×10^{-3}	1.29×10^3	1.07×10^{-8}	7.96×10^{-3}	3.12×10^3	9.62×10^{-8}
7	28	1.58×10^{-3}	9.51×10^2	2.68×10^{-8}	3.17×10^{-3}	2.30×10^3	2.42×10^{-7}
8	27	6.31×10^{-4}	7.00×10^2	6.72×10^{-8}	1.26×10^{-3}	1.67×10^3	6.08×10^{-7}
9	26	2.51×10^{-4}	5.15×10^2	1.69×10^{-7}	5.02×10^{-4}	1.24×10^3	1.53×10^{-6}
10	25	1.00×10^{-4}	3.79×10^2	4.24×10^{-7}	2.00×10^{-4}	9.15×10^2	3.83×10^{-6}
11	24	3.98×10^{-5}	2.79×10^2	1.07×10^{-6}	7.96×10^{-5}	6.82×10^2	9.62×10^{-6}
12	23	1.58×10^{-5}	2.05×10^2	2.68×10^{-6}	3.17×10^{-5}	4.95×10^2	2.42×10^{-5}
13	22	6.31×10^{-6}	1.51×10^2	6.72×10^{-6}	1.26×10^{-5}	3.64×10^2	6.08×10^{-5}
14	21	2.51×10^{-6}	1.11×10^2	1.69×10^{-5}	5.02×10^{-6}	2.68×10^2	1.53×10^{-4}
15	20	1.00×10^{-6}	8.17×10	4.24×10^{-5}	2.00×10^{-6}	1.97×10^2	3.83×10^{-4}
16	19	3.98×10^{-7}	6.01×10	2.82×10^{-3}	7.96×10^{-7}	1.45×10^2	9.62×10^{-4}

Visual Magnitude	Velocity km/sec	Asteroidal		
		Mass grams	Diameter μ	Flux Particles/ft^2-day
17	18	1.58×10^{-7}	4.42×10	2.95×10^{-2}
18	17	6.31×10^{-8}	3.25×10	2.82×10^{-1}
19	16	2.51×10^{-8}	2.39×10	2.14
20	15	1.00×10^{-8}	1.76×10	1.41×10
21	15	3.98×10^{-9}	1.29×10	7.59×10
22	15	1.58×10^{-9}	9.51	3.72×10^{2}
23	15	6.31×10^{-10}	7.00	1.90×10^{3}
24	15	2.51×10^{-10}	5.15	8.51×10^{3}
25	15	1.00×10^{-10}	3.79	3.39×10^{4}
26	15	3.98×10^{-11}	2.79	1.12×10^{5}
27	15	1.58×10^{-11}	2.05	3.39×10^{5}
28	15	6.31×10^{-12}	1.51	9.12×10^{5}
29	15	2.51×10^{-12}	1.11	2.14×10^{6}
30	15	1.00×10^{-12}	.82	4.68×10^{6}
31	15	3.98×10^{-13}	.60	9.12×10^{6}
32	15	1.58×10^{-13}	.44	1.74×10^{7}
33	15	6.31×10^{-14}	.32	3.02×10^{7}
34	15	2.51×10^{-14}	.24	4.79×10^{7}
35	15	1.00×10^{-14}	.18	7.08×10^{7}

TABLE A.1.- MAXIMUM PARTICLE SIZE REMOVED BY RADIATION PRESSURE

ρ	μ	ρ	μ	ρ	μ
.05	11.50	.75	0.77	4.00	0.144
.06	9.60	.80	0.72	4.25	0.135
.07	8.20	.85	0.68	4.50	0.128
.08	7.20	.90	0.64	4.75	0.121
.09	6.40	.95	0.61	5.00	0.115
.10	5.75	1.00	0.575	5.25	0.109
.15	3.83	1.25	0.460	5.50	0.104
.20	2.88	1.50	0.383	5.75	0.100
.25	2.30	1.75	0.329	6.00	0.096
.30	1.92	2.00	0.288	6.25	0.092
.35	1.64	2.25	0.256	6.50	0.089
.40	1.44	2.50	0.230	6.75	0.085
.45	1.28	2.75	0.209	7.00	0.082
.50	1.15	3.00	0.192	7.25	0.079
.55	1.04	3.25	0.177	7.50	0.077
.60	0.96	3.50	0.164	7.75	0.074
.65	0.89	3.75	0.153	8.00	0.072
.70	0.82				

ρ = particle density

μ = particle radius, microns

TABLE A.2.- LIMITATION TO PARTICLE LIFETIME: P-R EFFECT

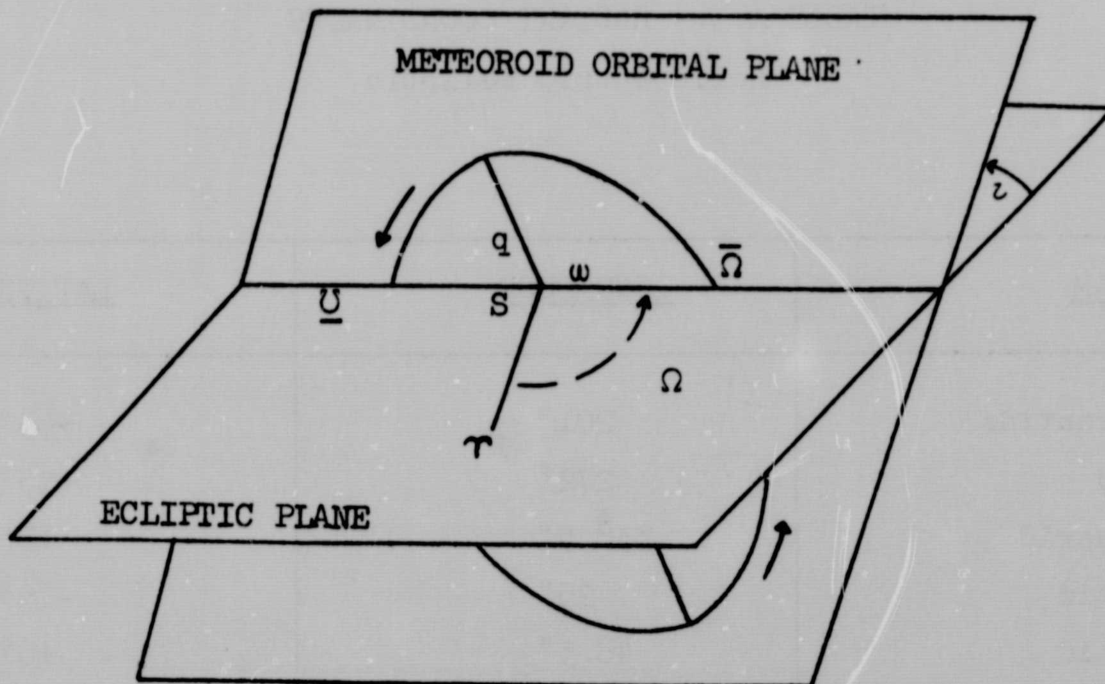
Particle of 0.5 gm/cm^3 Density and 2μ Radius

STREAM	PARTICLE LIFETIME, YEARS
Quadrantids	1.65×10^3
Lyrid	5.2×10^3
η-Aquarid	5.7×10^3
O-Cetid	95
Arietid	82
ζ-Perseid	5.2×10^2
β-Taurid	7.5×10^2
δ-Aquarid	84
Perseid	1.2×10^4
Giacobinid	3.4×10^3
Orionid	2.5×10^3
Arietid, Southern	4.9×10^2
Taurid, Northern	5.5×10^2
Taurid, Southern	7.1×10^2
Leonid	8.4×10^3
Bielid	2.95×10^3
Geminid	1.4×10^2
Ursid	2.4×10^4

TABLE A.3.- RADIANT COORDINATES

Heliocentric Ecliptic

STREAM	LONGITUDE	LATITUDE
Quadrantids	201°	+63°
Lyrid	272°	+55°
η-Aquarid	338.5°	+8°
O-Cetid	25°	-15°
Arietid	48.5°	+6°
ζ-Perseid	63.5°	+2°
β-Taurid	88°	-5.5°
δ-Aquarid	335.5°	-7°
Perseid	60.5°	+39°
Giacobinid	261°	+79°
Orionid	91°	-8.5°
Arietid, Southern	42.5°	-6°
Taurid, Northern	55°	+2°
Taurid, Southern	61°	-5.5°
Leonid	145°	+10°
Bielid	37.5°	+30°
Geminid	110.5°	+10°
Ursid	211.5°	+69°



♈ - heliocentric position of vernal equinox

ι - inclination of the meteoroid orbital plane to that of the ecliptic plane

Ω - longitude of the ascending node

ω - latitude of perihelion

q - perihelion distance

$\bar{\Omega}$ - ascending node

$\underline{\mho}$ - descending node

S - sun

a - semi major axis of the ellipse

e - eccentricity of the orbit

T - time of perihelion passage

π - (Ω + ω) longitude of perihelion

FIGURE 1.- ORBITAL ELEMENTS

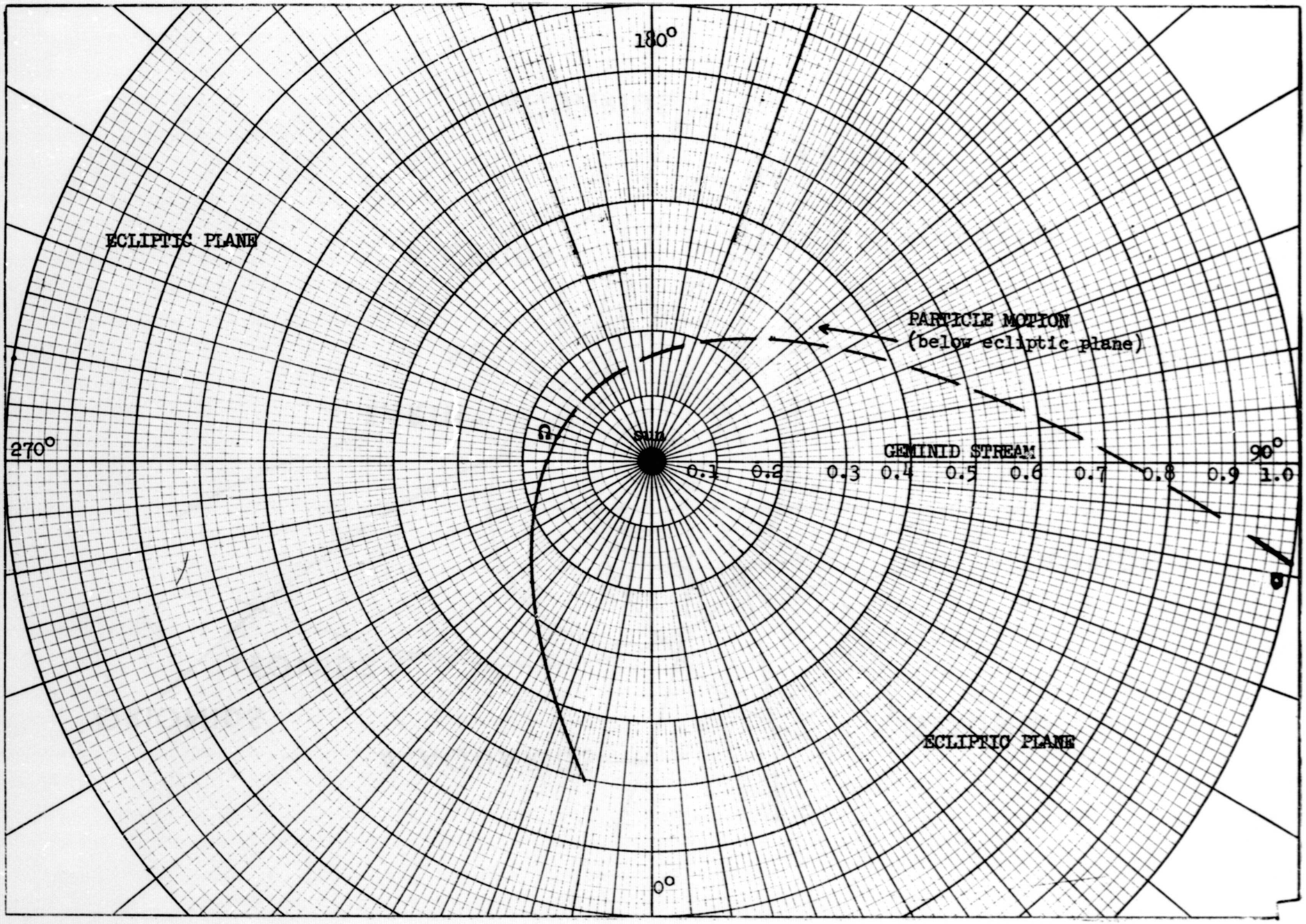


FIGURE 2.- GEMINID METEOROID STREAM

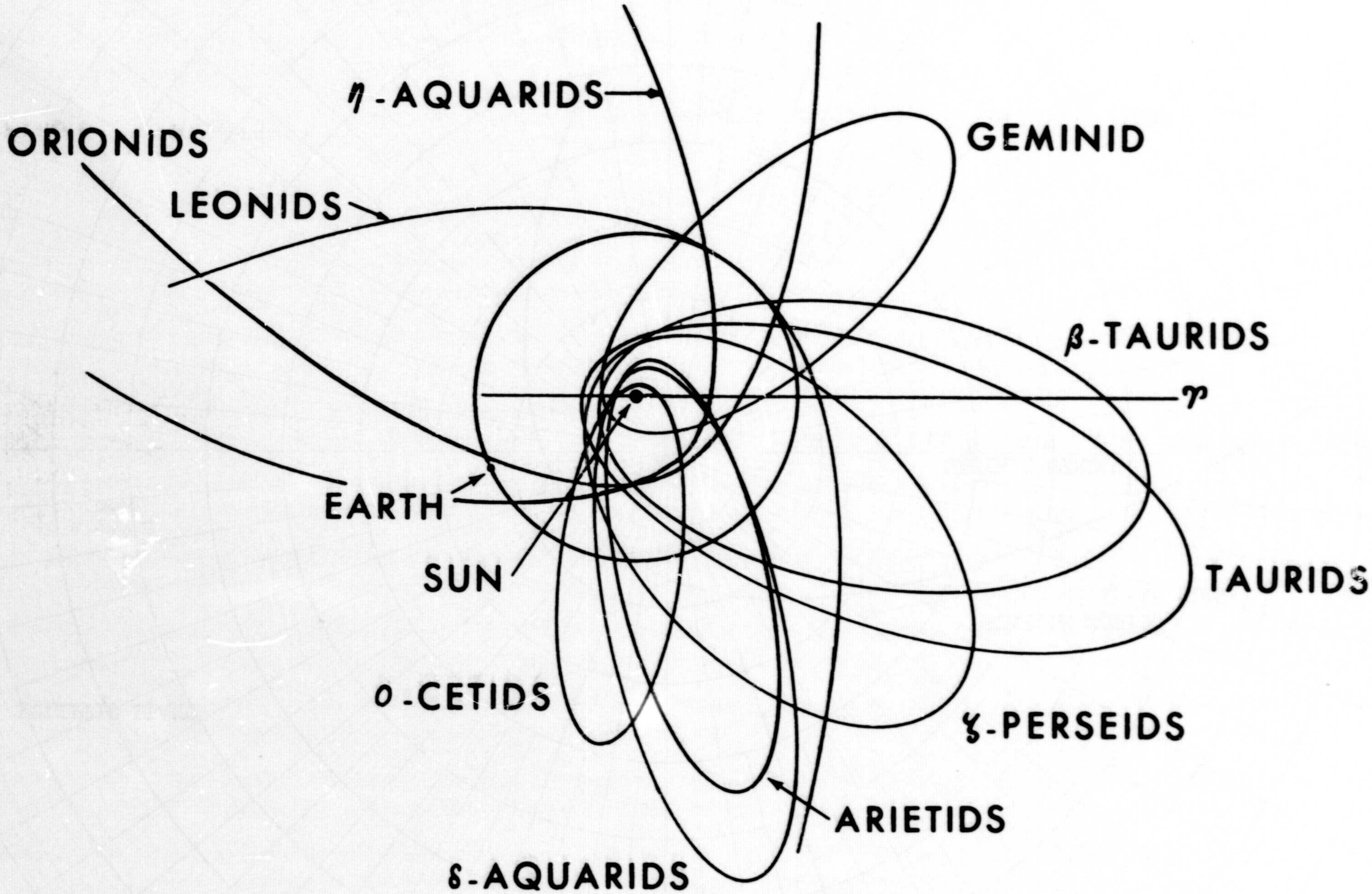


FIGURE 3.- METEOROID STREAM ORBITS

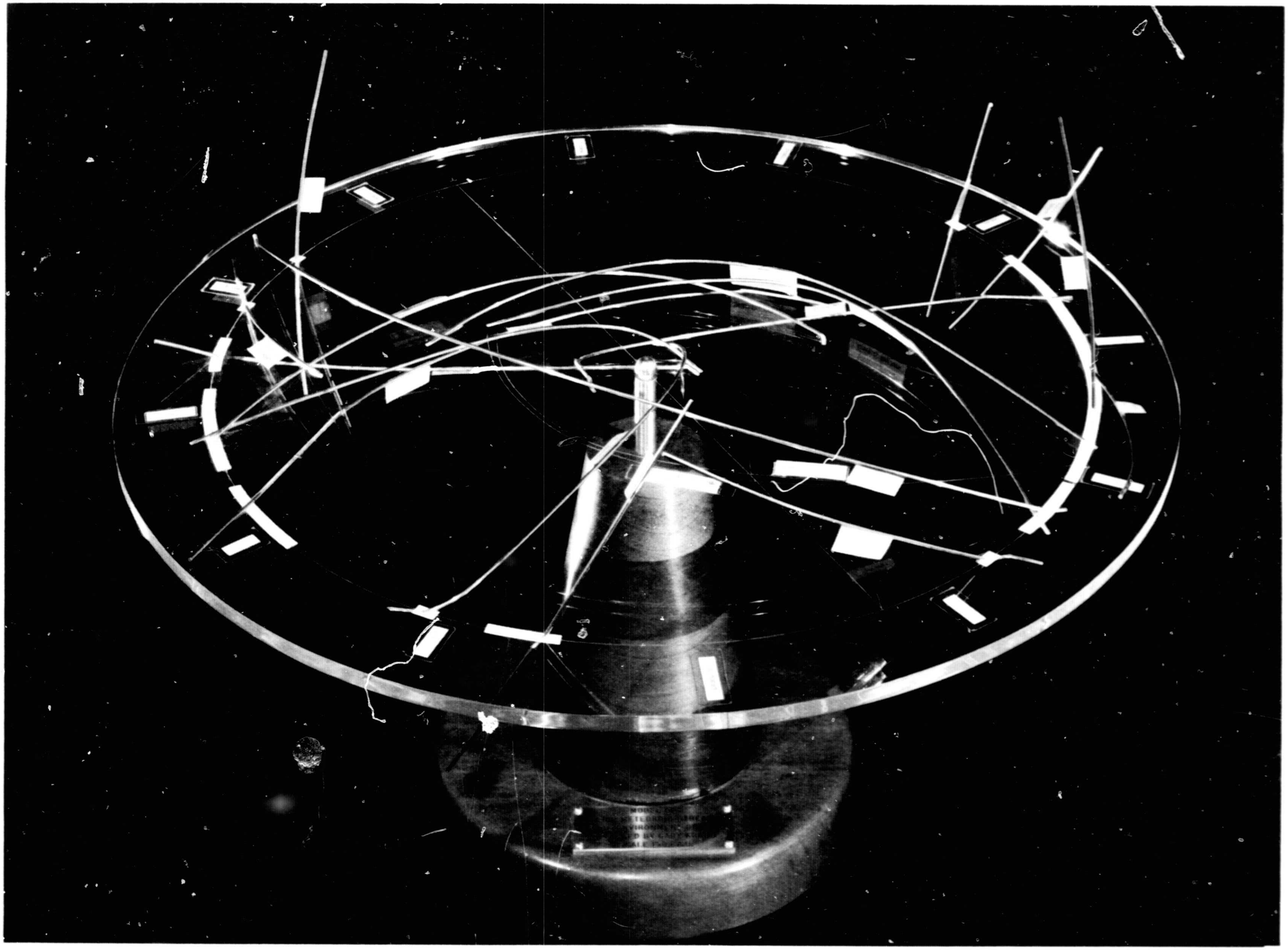


FIGURE 4.- MAJOR METEOROID STREAM MODEL

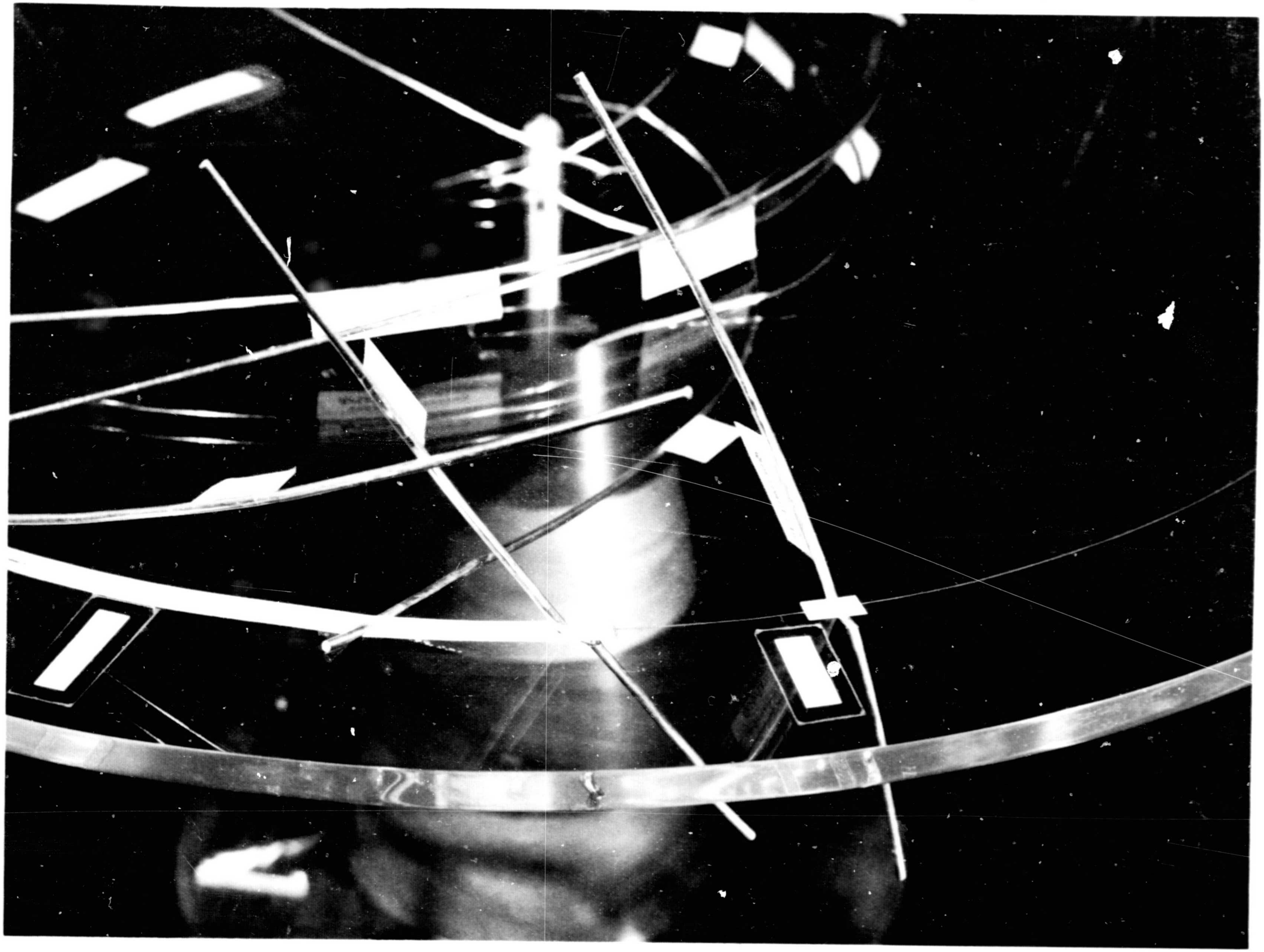


FIGURE 5.- CLOSE-UP OF MAJOR METEOROID STREAM MODEL