PART VI

METEORS AND PLANETS

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PAPER 72

SOME PROBLEMS OF METEOR ASTRONOMY*

INTRODUCTORY LECTURE BY

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We are now in an era of remarkable progress in the study of meteors. The electronic techniques developed at Jodrell Bank by Lovell, Clegg and others, and now by Davies, have culminated in giving us the power to observe the equivalent of 8th or 9th magnitude meteors for velocities, radiants and orbits. And certainly the limit has not yet been reached. The Harvard Super-Schmidt meteor cameras represent nearly the limit of current photographic-optical techniques; they approach close to the visual limit for very slow meteors, and with great precision, to 0·1 % in velocity and radiant.

I cannot take the time to review the subject of meteoric astronomy because too much has happened. I shall only mention the state of the art in certain areas of interest and point out some of the problems that I feel we should make special efforts to solve. These problem areas are as follows:

1. Meteor orbits and their generic significance.

2. The physics of persistent meteor trains and ionization.

3. The physics of the meteoric processes with special emphasis on the determination of meteoroid masses.

4. Possible atmospheric effects in the occurrence of radio, photographic and visual meteors.

5. Problems of faint radio meteors and micro-meteorites, including the Zodiacal Light and possible correlations with rainfall, the earth's magnetic field, etc.

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We may now accept as proven the fact that bodies moving in hyperbolic orbits about the sun play no important role in producing meteoric phenomena brighter than about the 8th effective magnitude. In the radio region, McKinley [1] at Ottawa and Lovell and his colleagues at Jodrell Bank have proved that the hyperbolic component lies below the 1 % level. The Harvard photographic programme provides a similar demonstration for the brighter visual meteors. Among the fireballs and meteoritic falls, the evidence presented first by H. A. Newton [2] and more recently by Wylie [3] and by Whipple and Hughes [4] is not quite conclusive but is very convincing.

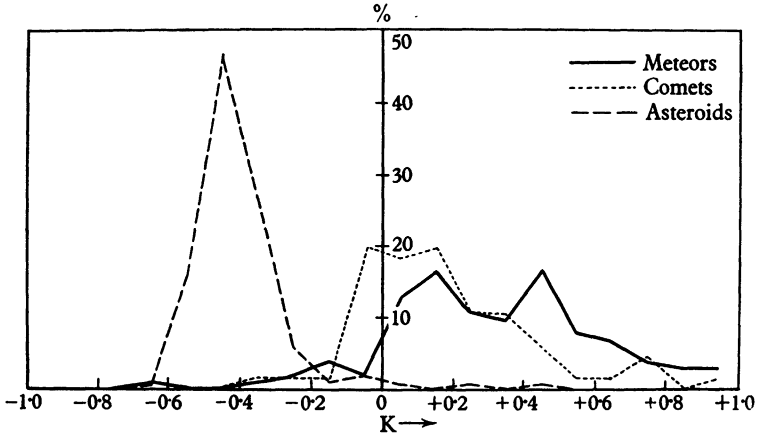

Fig. 1. Frequency of K criterion.

The major remaining difficulty at the moment, however, lies in discriminating between the meteoric contributions by comets and those by asteroids. The photographic orbits by Whipple [5] appear to be mostly (90 %) of cometary character, as judged by the arbitrary K criterion

$$\left[\log_{10}\frac{a(1+e)}{1-e}-1\right],$$

determined by the aphelion orbital velocity. Fig. 1 presents the frequency distribution of this quantity (for $K < +1$) for short-period comets, meteors and asteroids. Only two of the seven asteroids passing within the earth's orbit show positive values of K while all other asteroids except Hidalgo show negative values. Comets and meteors show largely positive values, with a similar distribution.

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The majority of meteors, whether photographic or radio, show a strong preference for direct motion near the ecliptic (or the invariant plane). Hawkins has shown this in a radio survey of sporadic radiant points [6] and Almond, Davies and Lovell [7] have shown with their apex and antapex experiments that the mean helio-centric velocity of radio meteors is about 34 km./sec., corresponding to an aphelion distance of 3 a.u. Jupiter's dominance is clearly indicated in the uniform distribution of aphelion distances of photographic meteor orbits between 3·0 and 6·5 a.u.

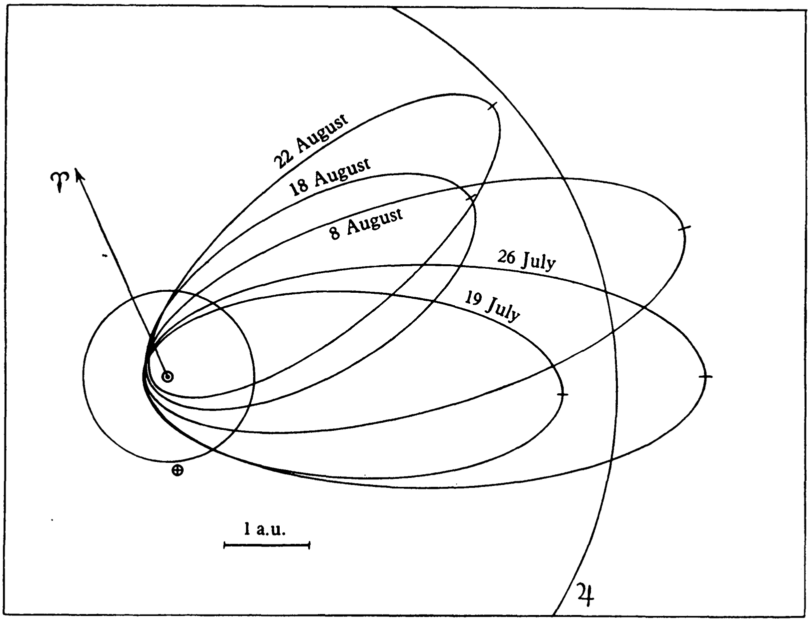

Fig. 2. Orbits of Southern Iota Aquarids.

Significantly, only one out of some 300 Harvard meteors has aphelion within the orbit of Mars (0·987 a.u.!, unpublished). This fact tends to support Öpik's conclusion that the earth has swept away any remnants of primitive asteroidal material crossing its orbit. Unfortunately the theory of the meteoric processes is still inadequate to distinguish chemically or physically between cometary and asteroidal meteoroids travelling in orbits with aphelia in the asteroid belt. A small fraction of the sporadic photographic orbits may well be of asteroidal origin.

Among the recognized meteor streams, however, the photographic evidence appears to rule out an asteroidal origin except possibly for the Geminids and the daytime *o* Cetids [8]. As shown in Table 1 and Figs. 2,

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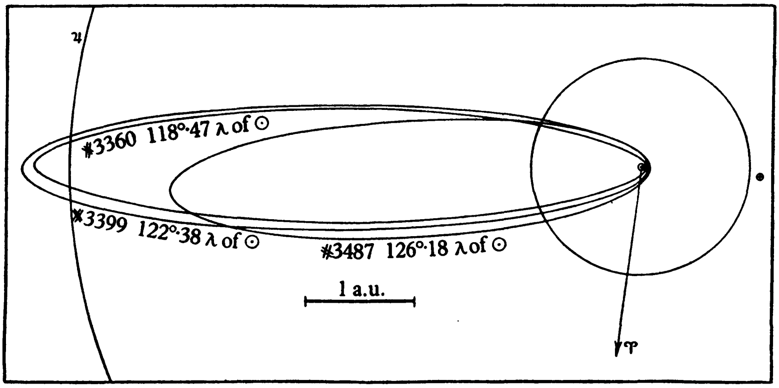

Fig. 3. Orbits of Delta Aquarids.

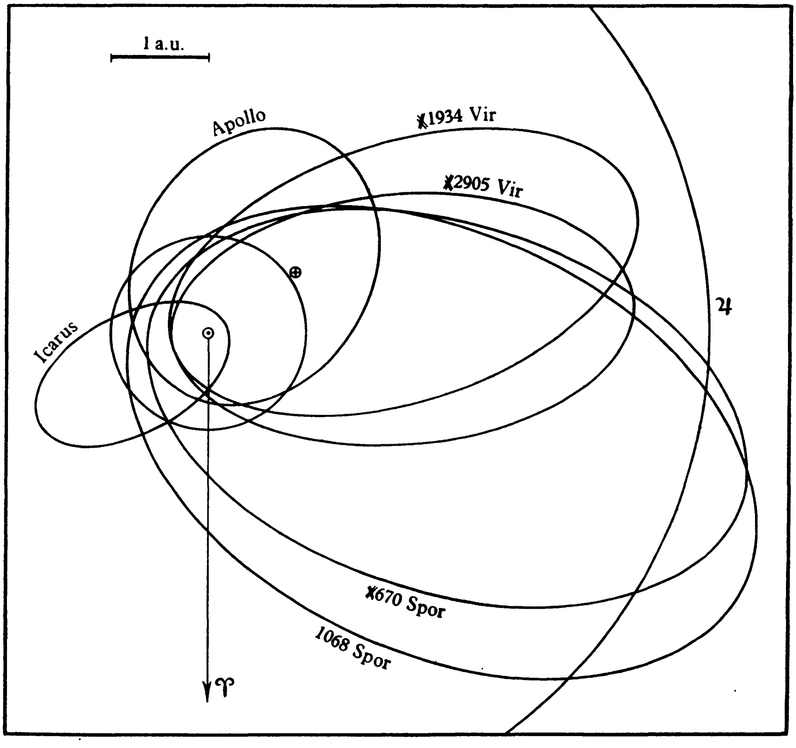

Fig. 4. Orbits of Meteors and Asteroids.

Table 1 presents a summary of the mean photographic orbital elements of all meteor streams determined from photographic data at present available at Harvard, along with the radiants for the streams, the date of maximum, in Universal Time, when possible, and the duration of the showers. The streams identified by Roman numerals are generally based on too few meteors to be immediately accepted as real, although the probability of such similarities in orbits is rather small (see Whipple [5]).

Table 1. *Mean orbital elements of meteor streams*

Stream	No. of orbits	V_∞ km./sec.	V_G km./sec.	V_H km./sec.	ϖ (°) 1950·0	Ω (°) 1950·0	i (°) 1950·0	π (°) 1950·0	a (a.u.) $1/\overline{(1/a)}$	e	P (yr.)	q (a.u.) $a(1-e)$	q' (a.u.) $a(1+e)$	Elong. (°)	U.T. date at max.	Duration (days)	Corr. radiant α ('50)	δ
Quadrantids	(1)	44·1	42·4	39·3	167·9	282·2	73·8	90·1	3·42	0·715	6·3	0·974	5·87	62·9	3 Jan:		230°	+48°
'I'	(2)	14·7	9·8	37·2	172·2	354·4	11·1	166·6	2·20	0·550	3·3	0·990	3·41	131·8	(14–17 Mar.)		57°	+69°
Virginids	(3)	30·8	28·9	38·3	285·8	353·7	5·2	279·5	2·82	0·857	4·7	0·403	5·24	81·4	(5–21 Mar.)		183°	+ 4°
'II'	(2)	15·2	10·6	37·8	187·1	27·3	11·0	214·4	2·67	0·626	4·4	0·999	4·34	134·4	(14–21 Apr.)		157°	+56°
Lyrids	(3)	48·4	47·0	41·6	213·9	31·8	79·9	245·6	29·6	0·969	161	0·918	58·3	61·0	21 Apr.		270°	+33°
ι Aquarids	(4)	35·75	33·82	37·93	127·5	311·0	6·0	78·5	2·88	0·920	4·9	0·230	5·52	73·4	(19 July–22 Aug.)	39:	338°	−14°
δ Aquarids	(5)	42·98	41·54	37·40	154·7	302·9	29·3	97·6	2·60	0·976	4·2	0·062	5·14	60·9	30 July	27	339°	−17°
α Capricornids (*a*)	(10)	25·53	23·02	37·45	270·5	132·8	4·0	43·3	2·57	0·779	4·3	0·568	4·57	89·9	1 Aug.	37	308°	−10°
α Capricornids (*b*)	(5)	25·05	22·50	36·97	270·5	122·5	7·2	33·0	2·35	0·755	3·6	0·576	4·12	90·0	(July α Capricornids)			
α Capricornids (*c*)	(4)	25·96	23·47	38·01	269·6	143·6	0·6	53·2	2·91	0·804	5·0	0·570	5·25	90·1	(Aug. α Capricornids)			
Perseids	(11)	60·44	59·30	41·29	151·2	138·1	113·7	289·3	20·8	0·955	95	0·936	40·7	39·8	12 Aug.	27	46°	+58°
κ Cygnids	(4)	26·6	24·2	39·2	204·2	144·3	37·0	348·4	4·09	0·762	8·3	0·973	7·21	93·4	(19–22 Aug.)		Incomplete	
'IV'	(2)	40·4	38·8	37·4	146·1	331·9	21·0	123·8	2·51	0·958	4·0	0·105	4·91	64·8	(21–29 Aug.)		0°	− 7°
'V'	(2)	22·2	19·4	39·8	203·8	192·9	26·4	36·6	4·66	0·794	10·1	0·960	8·36	106·2	(4–9 Oct.)		307°	+48°
So. Arietids	(1)	31·4	29·5	36·3	122·2	27·2	6·0	149·5	1·91	0·845	2·6	0·296	3·52	75·3	(15–27 Oct.)		42°	+10°
Orionids	(2)	66·5	65·5	40·8	86·8	29·8	163·2	116·5	7·70	0·930	21	0·539	14·86	26·1	22 Oct.	14	94°	+16°
So. Taurids	(5)	30·2	28·1	37·4	111·9	45·1	5·4	156·9	2·30	0·835	3·5	0·380	4·22	79·9	1 Nov.	32	51°	+14°
No. Taurids	(3)	31·3	29·5	37·0	298·4	221·8	3·2	160·2	2·14	0·849	3·1	0·323	3·96	77·1	17 Oct.–2 Dec.	47	52°	+21°
'VI'	(2)	21·3	18·5	39·0	65·3	43·4	6·0	107·8	3·34	0·776	6·1	0·748	5·93	104·4	(6–7 Nov.)		30°	+ 6°
					242·4	224·4											22°	+27°
Leonids	(5)	72·0	70·8	41·5	173·7	235·0	162·5	48·7	12·76	0·924	46	0·970	24·6	10·2	17 Nov.	6	152°	+22°
'VIII'	(2)	30·4	28·4	38·0	289·2	257·2	1·6	186·5	2·49	0·846	3·9	0·383	4·60	80·7	(9–10 Dec.)		86°	+24°
'IX'	(2)	24·5	21·9	37·4	88·2	79·0	5·0	167·1	2·22	0·740	3·3	0·577	3·86	90·4	(10–13 Dec.)		79°	+16°
'VII'	(3)	64·5	63·4	42·2	264·5	259·1	135·7	163·7	57·4	0·997		0·172		34·5	(8–13 Dec.)		151°	+33°
'X'	(2)	30·7	28·4	38·7	105·4	79·8	3·0	185·2	2·92	0·859	5·0	0·412	5·43	82·4	(10–14 Dec.)		88°	+20°
Monocerotids	(2)	44·0	42·4	42·6	128·2	81·6	35·2	209·9	−84·4	1·002		0·186		69·4	(13–15 Dec.)		103°	+ 8°
Geminids	(19)	36·5	34·7	34·1	324·3	261·2	24·0	225·6	1·39	0·899	1·6	0·140	2·64	62·8	14 Dec.	6	113°	+32°
Ursids	(1)	35·2	33·4	40·6	212·2	264·6	52·5	116·8	5·91	0·845	14·4	0·916	10·90	79·2	17 Dec.:		206°	+80°

: = doubtful.

V_∞: Velocity in the atmosphere relative to the station after correction for atmospheric resistance.
V_G: Velocity relative to the centre of the earth after correction for diurnal rotation and the earth's attraction.
V_H: Velocity relative to the sun after correction for earth's motion and attraction.
Orbital elements: i, a, e, P, q and q' denote, as usual, the inclination, semi-major axis, eccentricity, period, perihelion and aphelion; while ϖ, Ω and π give the angle from the ascending node to the perihelion point, measured along the orbit in direction of motion, the celestial longitude of the ascending node as seen from the sun, and where π is the sum of ϖ and Ω, all referred to ecliptic and equinox of 1950·0.
Elongation is the angle between the corrected radiant and the apex of the earth's motion.

3 and 4 the October Arietids (daytime ζ Perseids), Taurids (daytime β Taurids), α Capricornids, ι Aquarids, Virginids, δ Aquarids and κ Cygnids all have their aphelia near Jupiter like the short-period comets. Hoffmeister's [9] use of the term 'ecliptic currents' for such streams has suggested an asteroidal generic connexion which the best orbital data do not support. We still require, however, objective physical criteria to eliminate all possibility of asteroidal origin for one or two of the recognized streams. Jacchia's [10] discovery that the Geminid meteoroids have either greater densities (2·5 times) or greater luminous efficiencies (10 times) than do average meteoroids leaves some element of doubt as to their true nature. It is difficult to find a mechanism whereby a comet could have attained the small aphelion distances of the Geminids or of the daytime o Cetids.

The writer, however, still prefers the working hypothesis that all meteor streams and almost all fainter meteors are of cometary origin. But we are badly in need of observational or theoretical methods whereby we can check this hypothesis critically.

2. THE PHYSICS OF PERSISTENT METEOR TRAINS AND IONIZATION

To date we have not even a rudimentary theory to explain the long persistence of radiation in a meteor trail. We can conclude only that the energy for the persistent radiation is derived from the meteoric process and not parasitically from the atmosphere by the introduction of foreign meteoric atoms. This conclusion follows from the well known fact [11] that faster meteors are much more efficient than slower meteors in producing long-enduring trains. Since slower meteors are more massive than faster meteors of the same brightness they should be better train producers than the faster meteors, if the parasitic hypothesis were correct.

Although it seems likely that active nitrogen stores the meteoric energy for the required seconds or minutes, nevertheless we need a detailed substantial theory of meteoric trains. Numerous checks on the theory are already available: the velocity dependence mentioned above, the strong variation in train-decay rates with altitude, knowledge of the physical parameters of the high atmosphere and even spectral information from Millman's [12] observation of a short-lived train between the shutter breaks of a meteor spectrum.

At Harvard we shall soon have much more statistical data on meteor trains and their height-decay rates [13], and hope to photograph train spectra directly. Relevant laboratory studies are badly needed to improve the theory. There is much to be done in this respect. I feel that a detailed understanding of persistent luminous trains will also involve a much improved understanding of the electron decay and diffusion observed in radio meteors. Millman [11] finds a strong correlation between the persistence of train luminosity and the persistence of electrons in meteor trails. The excellent foundation in this theoretical field by Lovell and Clegg [14], Herlofson [15], Kaiser and Closs [16], Greenhow and Hawkins [17] and others at Jodrell Bank must be extended and integrated with a theory of meteor trains to give a comprehensive understanding of the physical process occurring after a meteoroid has passed.

3. THE PHYSICS OF THE METEORIC PROCESSES

I have arbitrarily separated the present subject from the previous one for two reasons: (*a*) An important symposium of several days length on the Physics of the Meteoric Process occurred at Jodrell Bank last year, so there is no need to repeat or to condense these more prolonged discussions. (*b*) The problems of meteor-train physics appear more readily soluble than those of the general meteoric phenomena.

From radio and photographic observations we have now found numerical relationships, for meteors of a given velocity and brightness (or ionization), between the quantities meteoroid mass (m), meteoroid density (ρ_m), luminous efficiency and ionization efficiency. If any one of these four quantities can be determined, by any means whatsoever, the other three can be derived from our store of observations as a function of meteor velocity and brightness (or ionization). This peculiar situation arises from the nature of the 'drag equation' representing the observed decrease in velocity of the meteoroid caused by atmospheric resistance. When the other physical factors such as the drag coefficient (Γ), a dimensionless shape factor (A_0), and the atmospheric density ρ are approximated, observed, or derived theoretically we find that the measures of velocity (v) and deceleration $\left(\dfrac{dv}{dt}\right)$ give us the quantity $m^{1/3}\rho_m^{2/3}$ by the equation

$$m^{1/3}\rho_m^{2/3} = -\Gamma A_0 v^2 (dv/dt)^{-1} \rho. \qquad (1)$$

Had we even a semi-adequate theory for the production of light or of ionization in the meteoric process, we could determine the mass and hence, from equation 1, the density of a meteoroid. But no such theory exists. From the Harvard photographic data and the limiting assumption that *all* the kinetic energy is converted to radiation, I found [18] that the density of photographic meteors must be smaller than the density of stony meteorites. Since the luminous efficiency must certainly be much smaller than unity the densities must also be reduced. Jacchia [19] has found observational evidence for the fragility of meteoroids and Öpik [20] has presented theoretical evidence for their low densities.

Recently, A. F. Cook and I have found a more direct method for determining meteoric masses. In measuring high-altitude winds by the multiple photography of persistent luminous trains from two stations, we found an example in which the complete wind vector could be determined. The nearly vertical component down the meteor trail exceeded 40 m./sec., comparable to the horizontal wind velocities. There could be no doubt that this motion measured the transfer of momentum from the meteoroid to the surrounding air mass. With a suitable diffusion theory for calculating the momentum transfer Cook has calculated the mass, and, from equation (1), the density of the meteoroid. The density turns out to be 0·05 gm./cm.^{3}, on the basis of the most likely constants and theory. Its upper possible value, obtained by pressing all the uncertainties in the proper sense, appears not greater than 0·3 gm./cm.^{3}.

A few other examples of photographed trains that may give total velocity vectors are now under reduction. The present result should not be accepted as typical until we have had opportunity to confirm it thoroughly. Nevertheless, such a low meteoric density appears not inconsistent with other meteor theory and observation. The density of 0·05 gm./cm.^{3} leads to meteoroid mass nearly two orders of magnitude greater than those derived by the early Öpik theory. A zero (visual) magnitude meteor of velocity 28 km./sec. would have a mass of about 25 gm. The luminous and ionization efficiencies in terms of energy would be of the order of 10^{-4}. Such low values are quite reasonable when one considers the small atomic cross-sections for excitation or ionization by encounter.

Furthermore, a mass discrepancy discovered by van de Hulst [21] would be eliminated if small meteoritic bodies have such low densities. He calculated that the zodiacal cloud of small particles, if sufficiently extensive to produce the Zodiacal Light, should shower the earth by some 10^4 times the mass rate estimated by Watson [22] on the basis of Öpik's meteor theory. The increase in the meteoritic mass striking the earth discussed above will account for a factor of some 10^2. But van de Hulst determined the dimensions of the zodiacal particles, not their masses directly, so he had to assume meteoritic densities. Hence the density decrease of some two orders of magnitude in his calculation completes the removal of the 10^4 times discrepancy.

Cometary debris of extremely low mean density and of extremely fragile character is entirely consistent with the author's theory [23] for the icy comet model. That a simple cometary theory based on present-day estimates of the cosmic abundances of elements leads to a mean density for meteoroids of 0·3 instead of 0·05 gm./cm.^{3} cannot be considered a discrepancy. It seems that cometary debris must be made of imperfect crystals, full of holes at all dimensions from molecular to macroscopic.

The search, however, for independent methods of determining masses, densities, luminous efficiencies and ionization efficiencies for meteors must be pressed to the limit in order to clarify the basic problem of meteor physics.

4. POSSIBLE ATMOSPHERIC EFFECTS

A long-outstanding meteor problem was presented by Poulter [24] during the second Byrd polar expedition (1933–5). Poulter and a trained group of meteor observers found, near the South Pole of the earth, that with binoculars they could count some sixty times the normal frequency of meteors as compared with corresponding observations made at moderate latitudes. No explanation for this result has yet proved convincing. During the International Geophysical Year the observations will be repeated and perhaps the puzzle can be solved.

A new meteoric problem has recently come to light in the comparison of the radio and photographic ratios of meteor occurrence. Figs. 5 and 6 show, respectively, the mean hourly rates of night and daytime radio meteors averaged over each month for two years for sporadic meteors, with the major showers superimposed. The data are from Jodrell Bank, recorded by Hawkins [6] and Aspinall, at 72 Mc./s., uncorrected for astronomical theory but reduced to the total rate over the entire sky. The shower rates, averaged over the entire day, do not overwhelm the sporadic background. Both night and day rates show a maximum in June, July and August and a minimum in January, February, March and April. The summer/winter ratio is greater than three, exclusive of the major showers.

For comparison, the corresponding hourly rates of meteors doubly photographed by the Super-Schmidt meteor cameras in New Mexico are shown in Fig. 7. The averages for each lunation represent approximately 100 meteors, so that the statistical fluctuation is appreciable but not excessive. The seasonal variation is relatively small, certainly not exceeding a factor of 1·5 in the summer/winter ratio. Now, the photographic data are subject to variable discovery rates near the film limits due to changes in personnel. Also the blackening of the film by the Milky Way tends, somewhat, to reduce the sensitivity during the summer months. We are investigating these effects quantitatively but it seems worthwhile to present the preliminary raw data at this time, even though they are subject to some later correction.

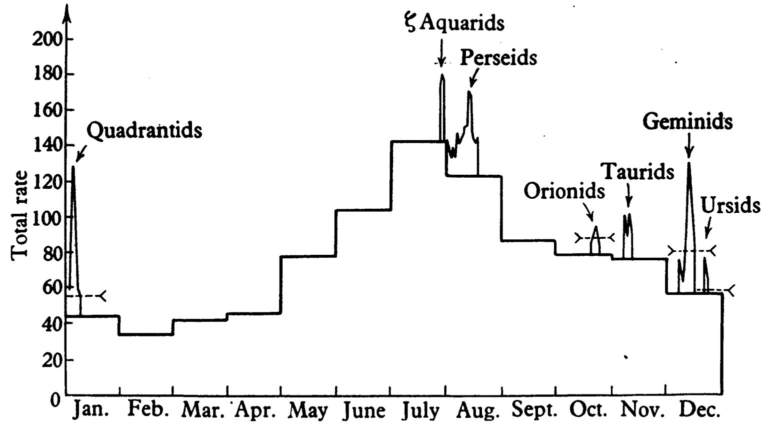

Fig. 5. Mean hourly rate of meteors for each night, showers and sporadic.

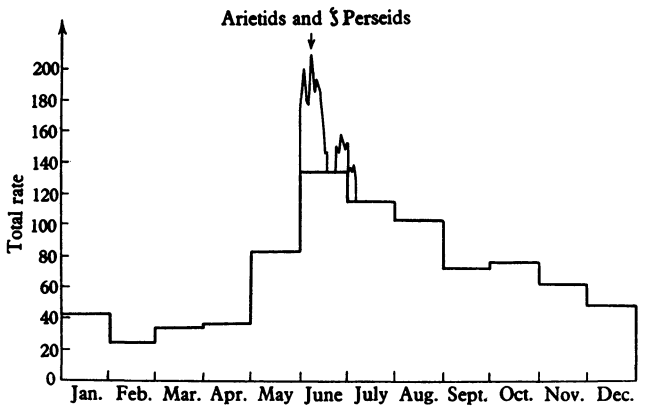

Fig. 6. Mean hourly rate of meteors for each day, showers and sporadic.

Unless the effects of Milky Way fogging or some other observational error are excessive, the yearly photographic meteor rates vary much less over the year than the radio rates. Three possibilities are obvious:

(1) The fainter radio meteors in space have a different orbital distribution from that of the brighter photographic meteors.

(2) Variations in the high atmosphere affect the radio rates seasonally,

in the sense that greater ionospheric activity may increase the ionization efficiency, reduce ion diffusion rates or reduce electron decay rates, etc.

(3) Meteors of different velocity groups may encounter the earth at seasonally variable rates and the differences in sensitivity as a function of meteoric velocity between radio and photographic methods may account for the observed seasonal difference.

One prefers to avoid the first possibility until the others have been thoroughly explored, first on basic principles and secondly because of the

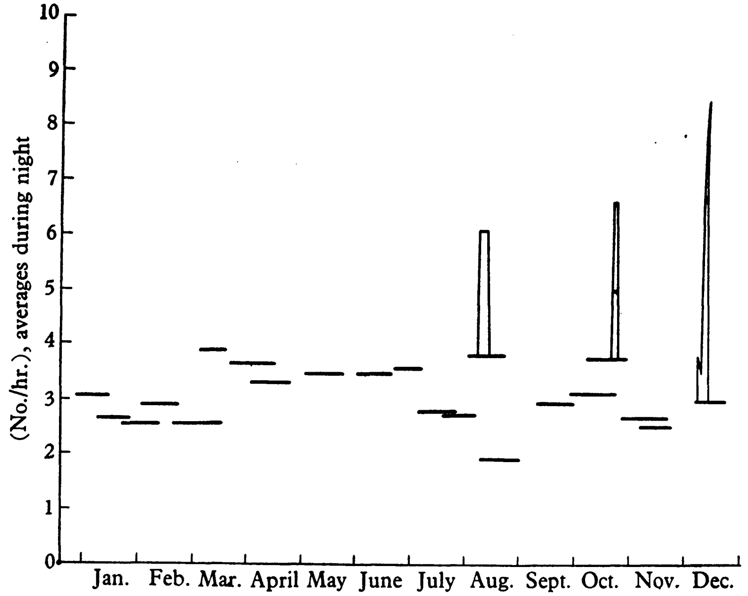

Fig. 7. Photographic meteor frequencies (no./hr.) for twenty-one lunations.

observation by Almond, Davies and Lovell [7] that the velocity distribution of radio meteors is independent of limiting magnitude.

The second possibility, an effect arising from seasonal changes in the ionosphere, could be readily checked by comparable radio observations from the southern hemisphere. The seasonal effect in meteor rates should remain, but be reversed with respect to the calendar months. Weiss [25], indeed, has published such radio meteor rates as observed in Australia, but the counts are not sufficiently numerous or well enough distributed over the year to be definitive. They appear, however, to show no change or possibly a slight increase during the southern summer as compared to the southern winter.

That the third possibility appears to operate in the required direction has been shown tentatively in the Harvard photographic studies. McCrosky [26] has completed the measurements, by a rapid graphical method, of about 1000 velocities for photographic meteors. The radio technique in meteor detection appears to be relatively more efficient than the photographic for meteors in the velocity range 25–50 km./sec. [27]. McCrosky's data show that photographic meteor rates in this velocity range do indeed show a seasonal variation like that of the Jodrell Bank radio meteors, but of smaller amplitude. Hawkins [6] has suggested that the seasonal effect may arise from a greater concentration of cometary orbits near the earth's orbit during the summer months, following Hoffmeister's statistics in this regard.

Whether or not the observational data are yet sufficiently firm to support the above arguments, we are in duty bound to clarify the matter. Systematic measurements of meteor rates from southern latitudes are essential. Furthermore we must all make every effort to ensure the validity of our statistics and the uniformity of measurement. Some important and surprising results with regard to the high atmosphere, to meteor physics or to meteor orbits may be in the offing.

5. PROBLEMS OF FAINT RADIO METEORS AND MICROMETEORITES

E. G. Bowen [28] has introduced a most fascinating problem in the area of micro-meteorites by his arguments that micro-meteorites produce condensation nuclei to trigger off unusually heavy rainfall about thirty days after certain meteor showers. Although statistical arguments against Bowen's theory have been presented by D. F. Martyn and others, Bowen has collected independent geophysical evidence for his hypothesis such that we in meteor astronomy cannot ignore his proposals. Millman [29] has outlined some of the meteoric difficulties involved and it is clear that some radical changes in our general concepts of meteoric astronomy are demanded by Bowen's hypothesis. We must investigate carefully to be certain whether these changes do or do not, in fact, violate our observations. Our theories, of course, have no intrinsic merit except as they integrate the observations.

In the meteor-rainfall correlations, certain meteor showers, such as the Geminids and the Quandrantids, must produce condensation nuclei in numbers that are markedly greater than in the sporadic background. But we see from Hawkins's data (Figs. 5 and 6) and the photographic data

(Fig. 7) that few ordinary meteor showers at maximum intensity exceed the sporadic background rate. Nor is there any indication that the shower/sporadic rate increases with decreasing particle size; in fact, Davies [30] finds just the reverse. Probably the radio meteor showers are less conspicuous against their sporadic background than the photographic showers of larger meteoroids. But below some particle dimension the showers must become overwhelmingly strong with respect to the sporadic rates if Bowen's hypothesis is true.

This postulate of powerful, as yet unobservable, streams of micrometeorites is further required by Bowen's [31] correlations of heavy rainfall with the Bielid and Draconid showers, which are only occasionally observed by visual, photographic or even radio techniques.

It appears that the meteor-rainfall hypothesis requires that relatively 'young' meteor streams carry with them an unobserved and excessive amount of fine dust, which, in space, does not survive to accompany statistically the sporadic meteoroids isolated or detached from meteor streams. Careful and detailed theoretical investigations will be required to ascertain the extent to which the above requirement is consistent with the observations of the Zodiacal Light, van de Hulst's [21] and Allen's [32] theory for it, and Whipple's [23] discussions of the dynamics of particles in the zodiacal cloud. The requirement of short-lived dust appears to be best explained by the erosive action of corpuscular radiation from the sun. Removal of dust from the streams by the Poynting-Robertson effect or the corresponding effect of corpuscular radiation appears not to be a solution to the problem. Whether or not the concentration of fine dust in meteor streams alone would produce such spatial irregularities as to cause *measurable* variations in the brightness or position of the Zodiacal Light requires further study. The meteor-rainfall hypothesis certainly leads to the necessity for variations in the Zodiacal Light; the only question concerns the amplitudes to be expected.

The above considerations, although sketchy and preliminary, indicate the need for new and more extensive attacks on the problem of micrometeorites. The methods range through (*a*) dust collection at all possible altitudes including the deep-sea oozes, (*b*) observations of optical scattering by dust in space and in the atmosphere, (*c*) more sensitive radio-meteor detection mechanisms, (*d*) geophysical measurements during meteor showers of possible concomitant effects in the ionosphere, in the earth's magnetic field or in other parameters, (*e*) laboratory and theoretical studies of the effects of corpuscular radiation on small particles, and (*f*) more extensive studies of the dynamics and physics of the zodiacal cloud. Whether or not Bowen's hypothesis is correct, these studies are needed to supplement the extensive research conducted on the larger meteoric particles.

Bumba's [33] interesting correlations between variations in the earth's magnetic field and the occurrence of meteor showers indicates the type of frontiers that may be opened up by such research.

Finally, another area of new possibilities is suggested by Davies' current measurement of orbits for faint radio meteors. Whereas the photographic meteor orbits appear representative of cometary orbits, as though the large photographic meteoroids had been injected by comets into these orbits, the faint radio meteors show a much greater preponderance of smaller, more circular orbits. If these radio orbits represent a systematic change in character from the 'injection' orbits, the cause most probably lies in the action of corpuscular solar radiation, which produces an effect similar to the Poynting-Robertson [34] spiralling effect. Since the larger meteoroids appear to be eliminated by collisions with zodiacal material [23], a knowledge of the meteoroid dimension at which spiralling occurs provides a measure of the mean momentum carried by corpuscular radiation. Meteoroid densities, of course, are also required in this solution.

Thus many problems of the interactions of radiation, corpuscular radiation and meteoritic material in the solar system appear to be soluble in the near future.

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Discussion

Lovell: Whipple's conclusion that meteors have such large diameters (25 cm. for zero magnitude) will have considerable repercussions on the theory of the scattering of radio waves by meteor trails. These theories are based on the idea that the diameter of the ionized trail is very small compared with the radio wave-length both at the instant of formation and for some time afterwards.

Whipple: But the radio meteors are much fainter; their diameters do not exceed 1 cm.

Greenstein: Would not all the peculiar variations in the distribution of the radio meteors have been smoothed out by the Poynting-Robertson effect if they had been going around so long?

Whipple: A good percentage at any time ought to be newly injected.

Gold: A density $< 0{\cdot}1$ is almost impossible to achieve with ordinary materials. It would have to be a body composed of long thin needles or threads. More compact pellets stuck together even with a lot of interspaces would result in a higher density. It is interesting to note that needles are also required for other purposes in interstellar space.

Whipple: I think indeed of an extremely fragile body from which all the ice has evaporated.