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THE BLUE HAZE OF MARS[1]

by

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The extent of blue clearings is investigated as a function of the number of the meteor showers intersecting Mars' orbit, at 10° intervals of heliocentric longitude. A rank correlation method has been employed. The analysis indicates a small but statistically significant negative correlation between the extent of blue clearing and meteor shower activity. This result combined with the optical properties of the Martian atmosphere and the close resemblance between the characteristics of the blue haze and those of the terrestrial noctilucent clouds suggests that variable amounts of interplanetary dust are suspended in the Martian atmosphere and that the occasional clearings of the blue haze are caused by a diminishing influx of these dust particles.

Author

INTRODUCTION

The characteristic optical properties of the Martian blue-absorbing haze observed during the past seventy years have evoked numerous hypotheses concerning its composition and mode of formation. As early as 1926 Menzel realized that the decreasing intensity toward shorter wavelengths of the light reflected by the Martian atmosphere is not due solely to molecular scattering but also to suspended particles having dimensions of the order of wavelengths of visible light and whose origin ought to be interplanetary space. Link (1950) first ascribed the observed properties of the blue haze to meteoritic dust and postulated further that the Earth, Mars, and Venus are likely to possess a dust layer in their upper atmospheres. Direct evidence has been obtained by Bouska and Svestka (1950) during 33 lunar eclipses that showed the dimensions of the Earth's shadow to exceed the theoretical values by about 2 %. Moreover, the increase in the Earth's shadow was found to be directly related to meteor shower activity (Link, 1962, pp. 202-206). Numerous optical measurements of Mars were performed in the interim and they all seemed to substantiate Link's hypothesis. The objections raised by de Vaucouleurs (1954), that the blue haze but not its occasional blue clearing may be accounted for in this manner, can be disproved on the grounds of nonuniform distributions of the particles causing the blue haze, as will be discussed subsequently.

THE ROLE OF INTERPLANETARY DUST

Recently Öpik (1962) re-examined the accumulated data and advanced cogent arguments that the optical properties of the blue-absorbing haze and its intermittent clearings accord with variable amounts of dust particles having dimensions of the order of 0.1 μ, and that absorb more in the blue spectral region than in the red. But contrary to Öpik's contention, these particles are not indigenous to Mars, since the very tenuous Martian atmosphere (25 mb, Kaplan et al., 1964) militates against a convective lifting of the particles from the ground into the upper atmosphere. In this communication we endeavor to substantiate Öpik's dust hypothesis and to demonstrate the interplanetary origin of these particles.

A phenomenon on Earth that appears to be relevant to the blue haze of Mars and that has been suggested as a possible counterpart by Deirmendjian and Vestine (1959), is that of the noctilucent clouds. Aside from their remarkably similar visual, photographic, and polarization properties (Dollfus, 1948), the spectra of noctilucent clouds recorded by Grishin and reduced by Deirmendjian and Vestine (1959) show a noteworthy correspondence with those of the Martian blue haze obtained by Wilson (1958). The peaks in the continuum represent minima and occur at λ 401, 425, 449, 469 mμ and maxima at λ 423, 434, 448, 463, 472, 480, 501 mμ, in the case of the blue haze and noctilucent clouds, respectively. The spectrum of the noctilucent clouds resembles that of daylight, inclusive of the Frauenhofer lines (Ludlam, 1957). Because of the possible analogy of the two phenomena, Wilson (1958) suggested that the particles may have a common interplanetary origin and may be comprised of cometary ice crystals. However, it is now widely accepted that the particles that cause the low reflectance of the Martian atmosphere in the blue spectral region ought to have a siliceous composition. Moreover, they are most likely accreted from interplanetary space for the reasons stated above. Since the uniform haze displays intermittent clearings, the particle source has to be variable in space and time as well as discontinuous.

The meteor showers through which Mars passes seem to constitute a most plausible source for such varying particle flux. The meteoritic dust hypothesis has been criticized because the slow rates of settling of dust particles (estimated to be of the order of years) are at variance with the observed rates of blue clearing. These may range from several days to several weeks, while reversing rates have been noted to be as rapid as four hours (Wilson, 1959). In the present mechanism of clearing of the blue haze, the rate-determining factor is the difference between the rate of precipitation and that of arrival of new dust particles at a given time. The particles settle out continuously, but the enhanced inflow beyond that due to sporadic meteors depends on the number and intensity of meteor showers intersecting Mars' orbit. While the total mass accreted from shower meteors may be only one-third that of the sporadic meteors, radio echo surveys of meteor activity have yielded peak rates identifiable with discrete showers. Rates varying from two to seven times background have been recorded (Lovell, 1954, pp. 391-393). Consequently, during minimum shower activity the particle density in the upper atmosphere should diminish as the number of particles being replenished is less than those settling out. Localized or planet-wide clearings will then ensue, depending upon the orbital elements and particle distribution of the meteor streams crossing the orbit of Mars.

STATISTICAL ANALYSIS

To substantiate this contention the frequency of occurrence of meteor showers has been compared with the extent of blue clearings. From the records of the Martian blue clearings obtained by E. C. Slipher at Lowell Observatory for the years 1926 through 1958, blue clearings as a function of heliocentric longitude have been determined. The average clearings observed at each opposition during a 10° interval of solar longitude are depicted in Fig. 1. The combined data, listed in Table I, have been used in the analysis. The measurements of 1960-61 reported by Robinson (1963) have also been included. The blue clearings are correlated with the number of showers, presented in Table II and plotted in the upper part of Fig. 1. The most reliably known dates, duration, and inclination of the permanent and periodic meteor showers are listed. The upper group represents the recurring cometary showers and the lower group is a set of permanent streams for which comets have not been identified. Order of magnitude calculations show that any meteor shower observed on Earth having a long duration and low inclination will intersect the orbits of both Earth and Mars. For example, a meteor shower having a cross-section of 0.5 a.u. and an inclination of 30° (the maximum inclination included in our analysis) will deviate by about 0.5 sin 30 or 0.25 a.u. from the ecliptic plane and hence will pass Mars within the period observed on Earth ± 14.5 days. The stream widths at Mars' orbital distance differ by $\pm$ 2.5 days for $i \simeq 5^{\circ}$, $\pm$ 5 days for $i \simeq 10^{\circ}$, and $\pm$ 10 days for $i \simeq 20^{\circ}$, where i denotes the orbital inclination with respect to the ecliptic plane. Fig. 2 illustrates the mean orbits, projected on the plane of the ecliptic, of summer daytime meteor streams intersecting the orbit of Earth and Mars (Lovell, 1954, pp. 317, 378).

The two sets of data given in Tables I and II have been analyzed statistically by a ranking method (Kendall, 1948). Spearman's coefficient of rank correlation

$$\rho = 1 - \frac{6 \sum_i d_i^2}{n^3 - n}$$

where d and n denote the difference in the ranks of the ith pair of observations and the total number of ranks, respectively, has been evaluated to obtain a measure of the correlation between the number of meteor showers and the extent of the blue clearing when ordered by heliocentric longitude. Upon arranging the meteor showers in the order of their frequency and the blue clearings in the order of their extent, some members cannot be distinguished and thus yield ties. The coefficient, corrected for tie ranks, assumes the form

$$\rho = 1 - \frac{\sum_i d_i^2}{1/6\,(n^3 - n) - (T + U)}$$

where

$$T = \frac{1}{12} \sum_t (t^3 - t) \quad \text{and} \quad U = \frac{1}{12} \sum_u (u^3 - u)$$

with t and u designating the consecutive tied members of the two quantities. A value of -0.26 has been found compared with +1 or -1 for perfect agreement or disagreement. The significance of getting this value, or worse, can be computed. For large n, which in this case is 35 (no observations seem to have been reçorded for the 150° - 160° interval of solar longitude), the frequency distribution approached the normal distribution, so that the significance of ρ is assessed by computing the quantity

$$z = \frac{\text{corrected}\left(\sum_i d_i^{\,2}\right) - \text{expected}\left(\sum_i d_i^{\,2}\right)}{\sqrt{\text{variance}\left(\sum_i d_i^{\,2}\right)}}$$

A value of 1.46 was found and the probability of getting as bad or worse a value of z is 0.073 for no correlation. Although this is now very small, we incline to attribute significance to the observed value of ρ.

There are a number of uncertainties in the observational data that readily explain the lack of a strong correlation. They arise principally from the assumption that the meteor showers sighted on Earth will also intersect Mars' orbit within the corresponding intervals of solar longitude, and from the obvious omission of those meteor streams that may cross the orbit of Mars but bypass that of Earth. The relative intensities of the meteor showers at Mars may differ from those at the Earth since the particle density may not be uniform along their orbits. In addition, the variable particle density near Mars' orbit, being close to the asteroidal zone, is likely to exceed that at the Earth's orbit. Moreover, the data of the blue clearings are also subject to personal judgment in estimating the true extent of the clearing. Although we had the privilege of using a consistent set of observations by E. C. Slipher, estimated intensities may be in error by 20% or more.

METEOR SHOWER HYPOTHESIS

In view of the inherent uncertainties in the basic data, the observed value $\rho = -0.26$, and the corresponding probability $P(z) = 0.072$, allow us to accept the hypothesis that there exists a negative correlation between the number of meteor showers and the extent of the blue clearing.

Hence the combined evidence, founded on visual, photometric, and polarization measurements of Mars, the spectral correspondence between noctilucent clouds and the Martian blue haze, the resemblance between the polarization properties of these clouds and those of the blue haze, and the recent findings by rocket soundings concerning the composition and extraterrestrial origin of the noctilucent cloud particles (Hemenway et al., 1964), together with the results of the preceding statistical analysis, leads to the conclusion that the blue-absorbing haze is caused by dust particles swept in by shower and sporadic meteors. The occasional clearings result from a decrease in the amount of dust suspended in the atmosphere. This ensues during periods of low meteor shower activity when the number of particles precipitating exceeds that accreting from interplanetary space. The selective observations of clearings at or near opposition are consistent with the fact that many oppositions observed during the past thirty-five years did not coincide with meteor showers, as illustrated in Fig. 1 Localized or planet-wide clearings of the Martian blue haze will never follow a precise time sequence since the meteor showers undergo attenuation and enhancement in time and space, depending upon the perturbations of their associated comets. In addition, particles of asteroidal origin may contribute to a nonperiodic increase in the particle flux.

Recently Kviz (1961) has revived the meteor shower hypothesis but he construed the role of the dust particles to be that of nucleating centers, as in the case of terrestrial rainfall, by suggesting that the extent of the blue clearing be directly related to the number of meteor showers crossing Mars' orbit. This is neither feasible under the conditions prevailing in the upper atmosphere of Mars, nor does it accord with the reflectivities that decrease toward shorter wavelengths. The negative correlation derived in the present statistical analysis appears to be reconcilable with the entire body of observational data, including the clearings noted repeatedly at or near an opposition (Slipher, 1962).

The considerable progress achieved by recent experiments in establishing the characteristics of the noctilucent clouds (Hemenway et al., 1964) will benefit greatly the elucidation of the Martian blue haze. In view of their likely analogy, it may be of interest to enumerate the properties that appear to be common to both phenomena. The particles comprising the noctilucent clouds and those suspended in the Martian atmosphere have an average size of the order of 0.1 μ ; they probably have a chondritic composition that would account for a greater absorbance in the blue than in the red spectral region. In the case of the noctilucent clouds, iron and traces of nickel have been detected (Hemenway et al., 1964). Both phenomena appear at high altitudes, although the level of the Martian blue haze is less certain than that of the noctilucent clouds, which appear at 80-90 km altitudes. A knowledge of these levels would provide corollary information on the relative densities and temperatures of the respective atmospheres. Due to the lower gravity on Mars ($0.38g_E$) and the reduction in solar heating by a factor of 0.43, the density of the atmospheres at these heights may not differ appreciably in spite of the 200-fold disparity in the surface pressures. Another feature displayed by both phenomena is their latitudinal distribution, or nonuniformity across the hemispheres, due to the dependence of the particle influx on the declination of the radiant of the meteor stream. For example, pronounced variations were recorded during the 1954 and 1956 oppositions. Observers in South Africa reported more extensive clearings than those at Lowell Observatory in the United States.

The possibility that the Martian blue clouds represent the counterparts of the noctilucent clouds, as has been suggested by Wilson (1959), does not conflict with the meteor shower hypothesis of the blue haze. Recent samplings have indicated that some 10% of the dust particles comprising the noctilucent clouds show a coating of ice derived from the Earth's atmosphere (Hemenway et al., 1964). Analogously, the blue clouds may consist of clusters of the same particles that give rise to the opacity of the blue haze, and a fraction of which may possess a coating of ice or dry ice, as has been conjectured by Goody (1957). Hence the link between the blue clouds and the blue haze appears to be equivalent to that between the noctilucent clouds and the Earth's dust layer (Link, 1962, pp. 198-202). A self-consistent explanation obtains thereby in which all four phenomena are attributed to interplanetary dust particles.

POSSIBLE RELATED SURFACE VARIATIONS

The meteor shower hypothesis appears also to be consistent with a number of changes observed in the color contrasts of the surface markings. The possible effects of dust particles on the optical properties of the surface features have been recognized earlier by Kuiper (1961, p. 33) and Dollfus (1961). Since the principal purpose in this communication is to set forth an explanation of the observed properties of the blue haze and the attendant clearings, the results of the numerous visual, photometric, and polarimetric observations will not be recounted; the reader is referred to recent reviews by Slipher (1962), Öpik (1962), and Dollfus (1963). For purposes of illustration we are citing some examples of marked changes that might have been caused by variable amounts of dust particles accreted from interplanetary space.

A modification was noted during the 1954 opposition when the usually bright region of Hellas seemed to be darker than at preceding or subsequent oppositions (Dollfus, 1963, p. 560). A relatively dense cloud of dust may have accumulated over these areas during periods of quiescent atmospheric conditions. In general, however, the prevailing temperature and atmospheric fluctuations seem to be sufficient to prevent the contrasting surface features from becoming submerged beneath a uniform veneer. The occasional decrease in the reflectivities of the polar caps may also result from a temporary accumulation of dust particles. As the wind disperses them, the original brightness will be restored. Inside the canals, thought to be characteristic of the areological surface structure, a variety of dark spots and patches have been detected on several occasions (Dollfus, 1961). They might be temporary deposits of dust concentrated in these local areas.

Seasonal changes in the albedo and the polarization of the light reflected off the dark areas may also be attributed to the periodic increase of the inflow of dust particles during Mars' passage through meteor showers. The greatest number of meteor showers observed on Earth during the intervals of 115° to 146°, and 220° to 246° heliocentric longitude, is likely to manifest itself on Mars too, and consequently blue clearings should reach a minimum at these times. It has already been proposed that the apparent seasonal changes on the surface and the blue clearings may possibly be related and merit investigation by means of fly-by or orbiting probes (Sagan, 1963). In Depressio Hellespontica, seasonal changes in the albedo appear to be prominent and intermittent shifts in the degree of polarization of light reflected off dark areas have been noted in autumn and winter, and again in late spring (Dollfus, 1961). These properties, generally ascribed to alterations in the texture and photo-absorptivity of the surface material, would be consistent with a temporary accumulation of dust particles. Öpik (1962) has shown that a 25% decrease in transparency of the intervening atmosphere suffices to obscure contrasting surface detail. Consequently, a layer of differentially absorbing siliceous material that has accumulated locally will enhance the contours of the affected area compared to the dust-free bright surroundings. In contrast, a thin layer of dust may not reduce perceptibly the intense light reflected principally from the bright areas. This may account for the paucity of reports on recurring changes displayed by bright regions. According to the present view the reality of surface changes caused by varying climatological conditions is not discounted, but the temporary accumulations of dust particles represent an equally plausible, perhaps concurrent, cause for the random and seasonal color changes.

The meteor shower hypothesis would also not be inconsistent with Wright's diameter differential in the red and blue light. Differences as large as 3% have been reported, although the latest measurements performed at the June 1954, September 1956, and November 1958 oppositions by Dollfus and co-workers (1962) did not reveal such discrepancy.

EFFECTS OF SOLAR FLARES

While the mechanism of the blue clearings can be explained satisfactorily by the meteor shower hypothesis as described in the preceding discussion, possible effects on the Martian atmosphere induced by solar events have been investigated. In particular, interrelations between blue clearings and solar flares have been explored. The solar flare data were culled from well-known sources: the I. A. U. Quarterly Bulletin, and the NBS-CRPL Bulletin, Series F. Plots of solar flares of importance 2 and 3+, and additional ones including flares of importance 1, versus extent of blue clearings for the period 1926 through 1960 do not exhibit any significant correlation. Similarly, no ionization phenomena of the atmospheric constituents resembling cometary processes have ever been reported. The absence of such interdependence between Martian atmospheric events and solar flares may therefore be interpreted as indirect evidence for the existence of an areomagnetic field. Evidently, the solar plasma is staved off from close encounter with the atmosphere by a stream-forbidden zone generated by the permanent magnetic field.

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FOOTNOTE

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TABLE I

RELATIVE BLUE CLEARING PER OBSERVATION DURING A 10° INTERVAL OF HELIOCENTRIC LONGITUDES[a]

$\lambda_{\odot}$[b]	BC	$\lambda_{\odot}$	BC	$\lambda_{\odot}$	BC	$\lambda_{\odot}$	BC
0-9	35.7	90- 99	113.3	180-189	12.5	270-279	53.0
10-19	70.9	100-109	155.7	190-199	6.8	280-289	24.4
20-29	42.2	110-119	83.0	200-209	112.5	290-299	37.2
30-39	52.4	120-129	83.3	210-219	40.9	300-309	25.3
40-49	48.9	130-139	41.4	220-229	122.2	310-319	30.3
50-59	88.7	140-149	0.0	230-239	140.0	320-329	6.4
60-69	46.1	150-159	---	240-249	36.7	330-339	86.2
70-79	23.6	160-169	0.0	250-259	52.3	340-349	30.0
80-89	26.5	170-179	0.0	260-269	40.0	350-359	68.3

[a] Based on the observational data of E. C. Slipher, Lowell Observatory, Flagstaff, Arizona, for the period from 1926 through 1958, and those of J. C. Robinson, New Mexico State University, for 1960-61.

[b] $\lambda_{\odot}$ = Heliocentric longitude; BC = blue clearing.

TABLE II

MAJOR LOW INCLINATION METEOR SHOWERS[a]

Shower	Maximum activity[b]			Duration				
	$\lambda_\odot$	date	rate	$\lambda_\odot$	date	q' [c]	e	i
β Taurids	277	6/29	27	273-284	6/24- 7/6	4.11	.85	6
Capriconids	324	8/17	10	308-328	7/17- 8/21	5.30	.808	0.7°
S. Taurids	0	9/24	< 5	352- 64	9/15-11/26	3.09	.831	2
N. Taurids	30	10/24	< 5	24- 70	10/17-12/2	4.19	.877	3.8
Andromedids	46	11/9	< 5	40- 60	11/2 -11/22	4.64	.72	6.8
Virginids	174	3/16	< 5	164-181	3/5 - 3/21	5.02	.86	5
Arietids	257	6/8	66	248-267	5/29- 6/18	3.10	.94	21
ζ Perseids	258	6/9	42	250-265	6/1 - 6/16	2.85	.79	0
S. ι Aquarids	305	7/29	--	293-332	7/16- 8/25	3.04	.851	4.8
N. ι Aquarids	331	8/25	--	293-332	7/16- 8/25	3.22	.842	4.7
S. δ Aquarids	298	7/21	34	298-322	7/21- 8/15	5.85	.983	29.4
N. δ Aquarids	319	8/12	34	291-326	7/14- 8/19	5.17	.973	20.4
Monocerotids	78	12/10	--	65- 83	11/27-12/15	83.9	.997	24.8
χ Orionids	78	12/10	--	77- 82	12/9 -12/14	4.84	.848	0.9
Geminids	81	12/14	80	75- 83	12/7 -12/15	2.58	.896	23.6

[a] After Jacchia, L. G. (1963). Meteors, Meteorites and Comets. In "Solar System" IV (B. M. Middlehurst, and G. P. Kuiper, eds.), pp. 788 and 790. Univ. of Chicago Press, Chicago.

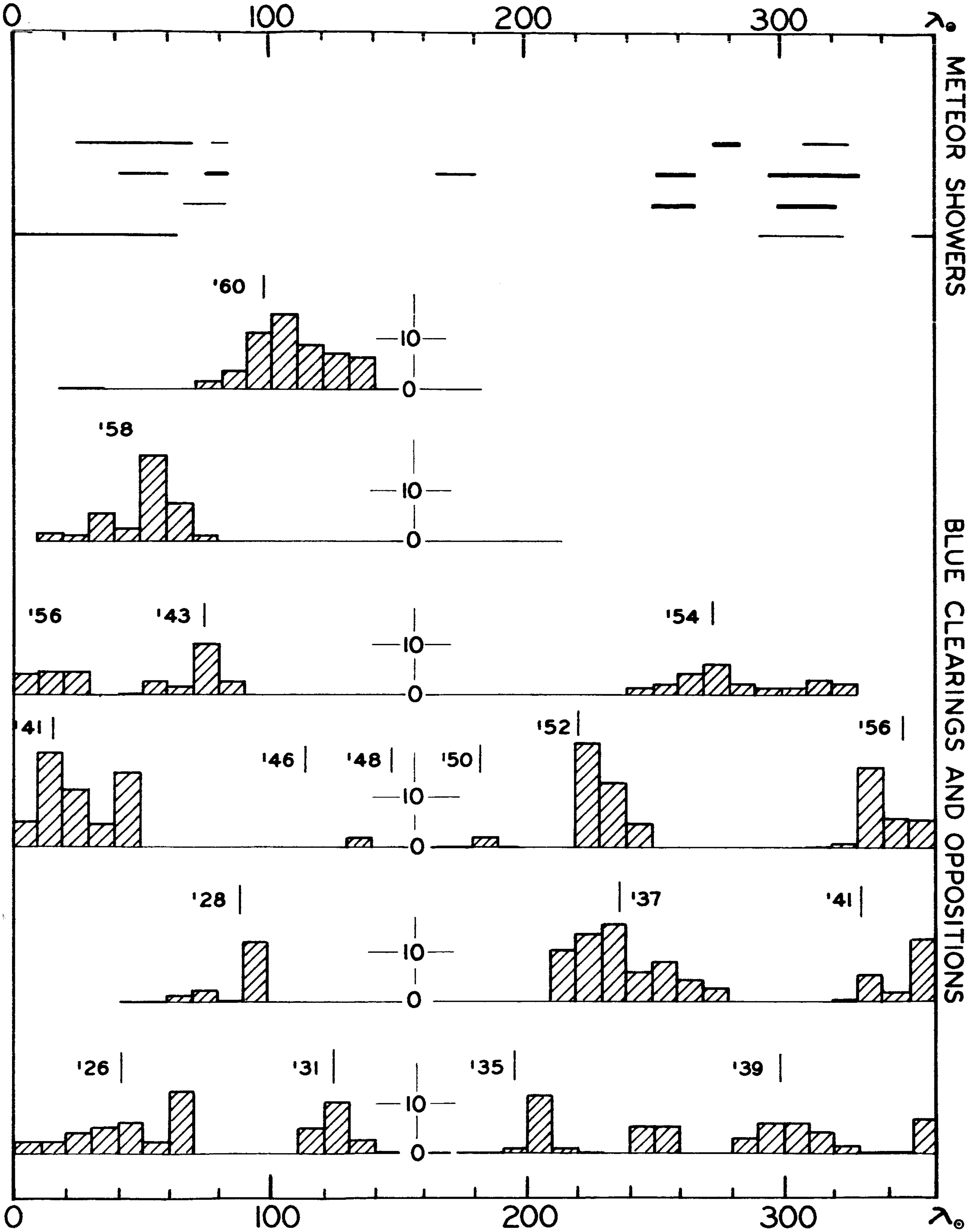
[b] $\lambda_\odot$ = Heliocentric longitude; hourly radio rate at maximum activity; q' = aphelion distance, a.u.; e = eccentricity; i = inclination.

[c] After Whipple, F. L., and Hawkins, G. S. (1959). Meteors. In "Handbook of Physics" 52 (S. Flügge, ed.) p. 545. Springer Publishers, Berlin.

LEGEND FOR FIGURES

Fig. 1. The average blue clearings observed at each opposition during a 10° interval of heliocentric longitude, longitudes of the corresponding opposition, and the duration of the relevant meteor streams. The line thickness indicates relative hourly rates at the Earth's orbit.

Fig. 2. Mean orbits of representative meteor streams projected on the plane of the ecliptic.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METEOR SHOWERS
BLUE CLEARINGS AND OPPOSITIONS
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Figure 1

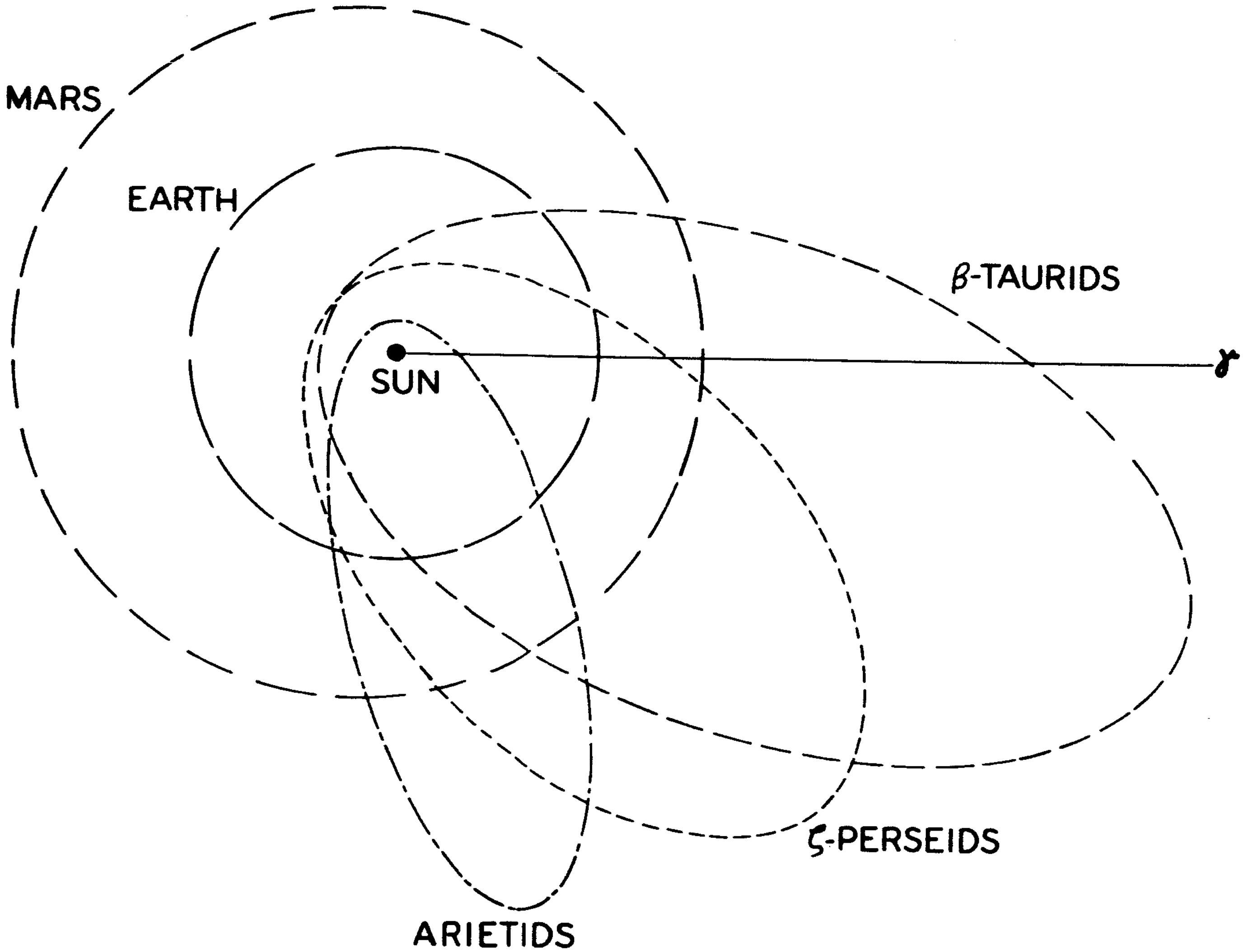

Figure 2