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MULTIPLE FALL OF PŘÍBRAM METEORITES PHOTOGRAPHED
V. THE ASSOCIATION OF THE PŘÍBRAM FALL WITH THE σ LEONID STREAM

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An association of the Příbram meteorite fall with the σ Leonid meteor stream is suggested and discussed. The comparison of the orbital elements, and the application of the Southworth-Hawkins and Tisserand criteria yield strong evidence in favour of a genuine association. On the other hand, it is difficult to reconcile the stream-membership with the cosmic-ray-exposure age of the meteorite determined by Stauffer and Urey. Although the possibility of a chance association cannot be entirely rejected, the results cast doubts on Mason's suggestion that chondritic meteorites have always been independent and individual objects.

Метеоритный дождь Пржибрам сфотографирован. V. *Связь метеоритного дождя Пржибрам с метеорным потоком σ Леонид*. Рассматривается вопрос о связи метеорита Пржибрам и потока σ Леонид. Сопоставление элементов орбит и применение критериев Саутуэрта-Хокинса и Тиссерана является веским доказательством в пользу подлинной связи. С другой стороны, трудно совместить принадлежность к потоку с возрастом метеорита, определенным Штауфером и Юри по длительности космического облучения. Хотя и нет возможности целиком исключить случайный характер орбитальной связи, результаты все-же ставят под вопрос правильность предположения Мейсона, по которому хондриты с самого начала являются независимыми и индивидуальными объектами.

The orbital elements of the Příbram meteorite have been computed by Ceplecha (1961) from double-station photographs; the accuracy of the determination is considerably higher than for any other meteorite fall yet observed.

A comparison with the orbits of photographic meteors reveals a remarkable similarity to the σ Leonid stream. This stream was recently recognized by Southworth and Hawkins (1960) in their statistical analysis of a random sample of 360 Super-Schmidt meteors, and is peculiar in two respects. Firstly, it is the stream of by far the greatest population within the sample, including

Table I
The elements

	Mean orbit of σ Leonids	Meteor No. 7135	Meteor No. 7218	Meteorite Příbram	Average σ Leo — mean orbit	Příbram — mean orbit
a	2·43	2·77	2·58	2·42	$\pm$ 0·62	$-$ 0·01
e	0·670	0·688	0·682	0·674	$\pm$ 0·080	$+$ 0·004
i	2·2°	8·9°	4·9°	10·4°	$\pm$ 5·4°	$+$ 8·2°
Ω	359·0°	19·1°	21·0°	17·1°	$\pm$23·0°	$+$18·1°
π	250·8°	247·6°	257·4°	258·7°	$\pm$17·3°	$+$ 7·9°

27 members, or 7·5% of the whole year's total and 40% of the meteors photographed in February and March. None of the other newly-found streams includes more than 9 members in the sample, and even the most abundantly represented major stream of Geminids has only 16 members. Secondly, the dispersion of the σ Leonids, active from February through May, is considerably greater than for any other known stream. Southworth and Hawkins suggest that the stream is certainly composite and that an improved test may possibly separate it into independent parts. There is some resemblance to the Taurid-Arietid complex, except that the separation into sub-streams is not apparent, at least on the basis of available data and criteria.

Table I presents the elements of the mean orbit assigned to the σ Leonids by Southworth and Hawkins, the elements of two individual σ Leonid meteors of the sample (Harvard trails Nos. 7135 and 7218) agreeing best with the Příbram meteorite, and the elements of the Příbram meteorite. The last two columns indicate the mean deviations of the 27 photographic σ Leonids from the mean orbit in each element, and the corresponding deviations of the Příbram meteorite. It is seen that, except for a moderate difference in inclination, all elements of the Příbram meteorite are nearer to the mean elements of the σ Leonids than the elements of a typical recognized member of the stream. The similarity of the orbits is also evident from the adjoined figure where the projections of the orbits into the plane of the ecliptic are drawn.

In order to estimate the degree of reliability of a genuine association between the meteorite and the stream we may apply the Southworth-Hawkins criterion

$$D(A, B) \lesssim 0{\cdot}20$$

where

$$[D(A, B)]^2 = [e_B - e_A]^2 + [q_B - q_A]^2 + \left[2 \sin \frac{i_B - i_A}{2}\right]^2 + \sin i_A \sin i_B \left[2 \sin \frac{\Omega_B - \Omega_A}{2}\right]^2 + \left[(e_A + e_B) \sin \frac{\pi_B - \pi_A}{2}\right]^2$$

This criterion is rather conventional, but its utility was empirically established on known streams. For the major streams Southworth and Hawkins find an average value of $\overline{D} = 0{\cdot}06$, for the minor streams $\overline{D} = 0{\cdot}17$. For the σ Leonid stream they find $\overline{D} = 0{\cdot}29$, a value exceeding the limit adopted for genuine associations, however there are serial associations below the level of $D = 0{\cdot}20$ between individual members. As a matter of fact, the D values referred to the mean orbit exceed 0·13 for all 27 σ Leonid meteors and 0·20 for 70% of them, whereas e. g. for the pair No. 7135 and No. 7218 shown in Table I, D is as low as 0·10.

The computed values of D for each combination of orbits of Table I are given in Table II*). It is evident that the D-test is satisfied for each of the 6 combinations. The Příbram meteorite deviates from the mean orbits of the σ Leonids much less than a typical member of this stream. It is interesting to compare the differences with those within the Taurid-Arietid complex, in which all meteors are genuinely associated. One finds that the differences between the Příbram meteorite and the two selected σ Leonids are of about the same magnitude as the differences within the separate branches of the Taurid-Arietid complex, and much smaller than the differences between the individual branches. They are also approximately equal to the differences in the outer regions of the Perseid stream and are lower than those

*) It must be pointed out that the values in the second and third line do not agree with those given by Southworth and Hawkins (1960). The reason is that Southworth and Hawkins list for each stream the orbital elements with the average values of a and e, while for evaluating the criterion they take the average value of q instead of that corresponding to the listed values of a and e. Obviously, a combination of the averages $\overline{a}$, $\overline{e}$, and $\overline{q}$ does not generally correspond to any possible orbit. If we adopt the average of two elements and adjust the remaining one accordingly, we obtain a possible orbit, but even this need not be an observable orbit, i. e. an orbit crossing the orbit of the earth. A good example is the ν Draconid stream for which the mean elements a and e, listed by Southworth and Hawkins, yield $q = 1{\cdot}47$! It is not easy to decide which is the best definition of a mean orbit, but it appears most reasonable to determine a, e, and q from:

$$a = 1 : \overline{\left(\frac{1}{a}\right)}_{\text{obs}}$$

$$\frac{a(1 - e^2)}{1 \pm e \cos \omega} = r_{\text{♁}} \cong 1$$

$$q = a(1 - e)$$

The principle of definition of the mean orbit is immaterial in the case of compact major streams; it may, however, become important for a stream of considerable internal dispersion, like the σ Leonids. Their elements taken from Table II of Southworth and Hawkins and supplemented by the appropriate value of q are:

$$a = 2{\cdot}43\,, \quad e = 0{\cdot}670\,, \quad q = 0{\cdot}802\,.$$

The mean elements used by them for evaluating the D-test are

$$a = 2{\cdot}16\,, \quad e = 0{\cdot}670\,, \quad q = 0{\cdot}714\,,$$

and the mean elements computed from the above three formulae:

$$a = 2{\cdot}17\,, \quad e = 0{\cdot}667\,, \quad q = 0{\cdot}722\,.$$

The Southworth-Hawkins criterion for the pair Příbram vs. mean orbit yields $D = 0{\cdot}17$, 0·19, and 0·19, respectively, for these three sets of elements.

Table II
The Southworth-Hawkins criterion

pair	D
mean orbit — average σ Leonid	0·29 ± 0·10
mean orbit — No. 7135	0·14
mean orbit — No. 7218	0·10
No. 7135 — No. 7218	0·14
Příbram — mean orbit	0·17
Příbram — No. 7135	0·15
Příbram — No. 7218	0·10

within the Andromedid stream. Judging from these analogies, a genuine association of the bodies appears to be beyond doubt.

Since the aphelia of the σ Leonid orbits are not far from the orbit of Jupiter, it seems reasonable to assume that the perturbing action of this planet has been the main source of the differences between their elements. In this case the association of the bodies should appear in an approximately equal value of the constant in the Jacobi's integral for the restricted three-body problem Sun-Jupiter-meteor. This may be checked by the Tisserand criterion (1896):

$$C = \frac{1}{a} + \frac{2}{a_J^{3/2}} \sqrt{a(1 - e^2)} \cos i$$

where a_J denotes the radius of the orbit of Jupiter, assumed circular. The resulting values of the constant C, which do not appreciably differ from those found for typical short-periodic comets of Jupiter's family, are given in Table III. The agreement is again very satisfactory, the discrepancies between the Příbram meteorite, the mean orbit and meteors Nos. 7135 and 7218 being much smaller than among individual recognized members of the stream.

Table III
The Tisserand criterion

object	C
average σ Leonid	+0·64 ± 0·09
mean orbit	+0·61
No. 7135	+0·56
No. 7218	+0·58
Příbram	+0·60

Hence both orbital criteria indicate an obvious association between the Příbram meteorite and the σ Leonid stream. A fainter meteor moving in the same orbit as the Příbram meteorite would be undoubtedly classified as a σ Leonid, more typical than the majority of meteors assigned to the stream by Southworth and Hawkins. The close relation to orbits Nos. 7125 and 7218 suggests that the evidence of an association with shower meteors cannot be weakened by any separation of the stream into independent branches, based on future data.

This result is rather unexpected in the light of other evidence. The Příbram meteorite is a chondrite, and its cosmic-ray-exposure age was estimated at 12×10^6 years by Stauffer and Urey (1962). This may be interpreted either as a collision age (Eberhardt and Hess, 1960) or as an erosion age (Whipple and Fireman, 1959); however even in the former case it is definitely too much for a meteor stream. Even for the considerable dispersion of σ Leonids the perturbation effects would make an age three orders lower more acceptable. Also with regard

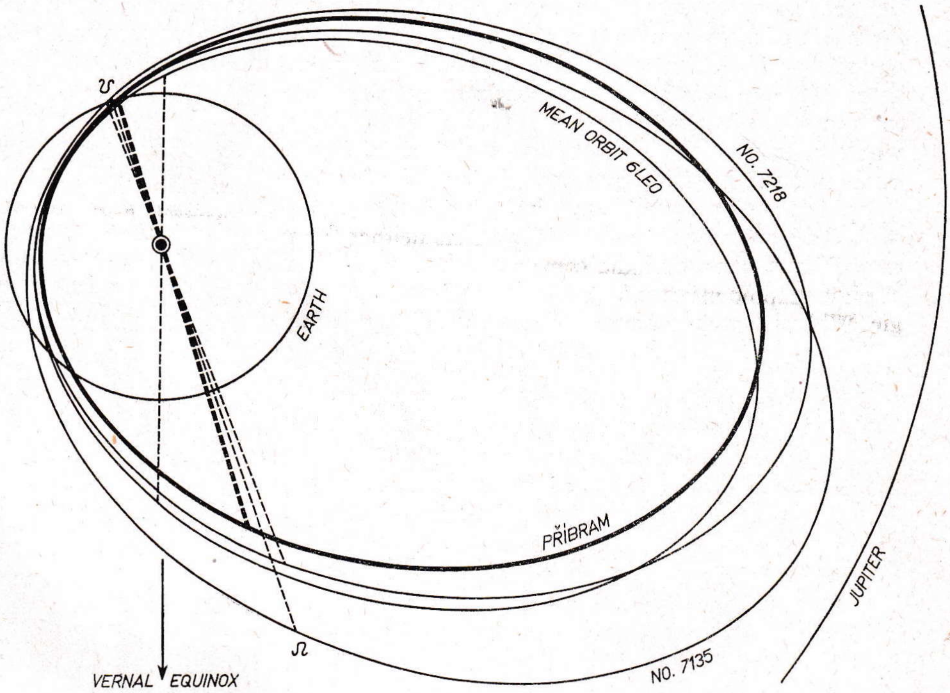

Fig. 1.

to the erosion in extraterrestrial space the photographic σ Leonids may hardly have existed as independent bodies for a period comparable to the exposure age of the Příbram meteorite. There are four possible explanations of this discrepancy.

(1) The exposure age is incorrect, because the source of the He^3 content is other than spallation by a persistent cosmic-ray bombardment of constant intensity.

(2) The mass of the Příbram meteorite was situated so near to the surface of the parent body that it was not shielded from cosmic rays for a long period before being injected into the present orbit as an individual body.

(3) For a period in its earlier history the Příbram meteorite was an individual object which, in some process of macro-accretion became a part of the parent body of the σ Leonid stream.

(4) The σ Leonid stream originated in an orbit, which by a curious chance coincided almost completely with

the orbit of the Příbram meteorite, and is not generically associated with it.

As there is no alternative explanation of the considerable He^3 content in the meteorite and also no appropriate accretion process known at present, explanations (1) and (3) are hardly admissible. Explanation (2) is possible in principle; however, in a body of the required size that might give rise to the extensive stream of σ Leonids only a very small part of the total mass may form the crust exposed to the cosmic-ray bombardment. Eberhardt and Hess (1960) estimate the depth corresponding to the range of the primary cosmic radiation at about 40 cm. Although the depth may be greater in a body of loose structure, attributed to cometary nuclei, even in this case the probability that a recovered meteorite will come just from the long exposed layer is very small.

Obviously, the relation to a comet would require that the exposure occurred in a long-periodic orbit and the formation of the stream until after a capture into a short-periodic orbit. A comet-meteorite association does not agree with the most frequently accepted opinion that meteorites are asteroidal débris. It is also irreconcilable with the assumption that cometary nuclei contain only small mineral particles immersed in an ice of frozen gases. It must be remembered, however, that the orbit of the Příbram meteorite essentially differs neither from the orbits of short-periodic comets nor from the orbits of photographic meteors believed to be of cometary origin. Whipple's comet-asteroid criterion (1954), applied to the meteorite, yields $K = +0{\cdot}10$. The possibility of the lunar origin of the Příbram meteorite has already been discussed by Stauffer and Urey (1962) who reject it just with regard to its eccentric orbit.

It is seen that it is very diffiicult to reconcile the cosmic-ray age of the Příbram meteorite with its generic relation to the σ Leonid stream. Nevertheless, a chance association of the orbits is also improbable, as was clearly demonstrated by the orbital criteria. Only further efforts at obtaining accurate meteorite orbits, comparing them with those of meteor streams, and determining the exposure ages of the meteorites concerned, may settle the problem with ultimate validity. A dependable explanation of the generic association between the σ Leonids and Příbram would be of considerable interest for the general problem of the origin of meteorites. Irrespectively of the process of formation of the stream it would contradict to the opinion of Mason (1960) that chondritic meteorites have always been independent and individual objects.

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