Theoretical meteor radiants for macroscopic Taurid Complex objects

D.J. Asher
Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia

and

D.I. Steel
Anglo-Australian Observatory, Private Bag, Coonabarabran, NSW 2357, Australia; and Department of Physics and Mathematical Physics, University of Adelaide, South Australia

Abstract
The calculation of theoretical meteor radiants is discussed for comets and asteroids whose orbits pass within, but at present do not necessarily intersect, that of the Earth, in particular from the perspective of developing a suitable method for application to Taurid Complex orbits. The main question addressed here is how to allow for dynamical evolution between epochs when an orbit is *not* Earth-intersecting (as at present in most cases for macroscopic bodies) and those when it *is* (*i.e.*, when meteors can actually be observed). This should be understood in terms of evolution in the past, such that meteoroids released some time ago have evolved differentially from the putative parents, allowing meteors to be detected now. Theoretical radiants for macroscopic Taurid objects are then presented and compared with observations of the nighttime and daytime Taurid meteor showers. These are found to be broadly similar in form, given the sparsity of some of the data, adding weight to the hypothesis that this sub-jovian complex contains kilometre-plus asteroids. A similar conclusion results for the group of objects in similar orbits to (2212) Hephaistos.

Key words: Taurids, orbital evolution, meteor radiants

1 The Taurid showers and the Štohl stream

By considering the meteoroidal mass released by comets and its orbital distribution, Kresák (1980) showed that the presently observable population of active comets is insufficient to maintain the zodiacal dust cloud in the inner solar system at its current density, while Olsson-Steel (1986) showed that the physical and dynamical evolution of the meteoroid and dust complex requires a major source in the recent ($\sim 10^4$ yr) past. Whipple (1967) indicated that the Taurid progenitor is likely to have been a substantial contributor to the zodiacal cloud, and Štohl (1980, 1984, 1986) demonstrated the existence of a broad sporadic stream of meteoroids, producing as many as half of all sporadic meteors, surrounding the main concentration of the Taurid meteoroid stream. This Štohl stream may be thought of as being the evolutionary stage prior to complete dispersal into the zodiacal background (Clube, 1987). Clearly a knowledge of its extent and behaviour is of paramount importance if we are to understand the ecology and present state of the small bodies in the inner solar system.

Before orbital diffusion into the broad Štohl stream, the population of Taurid Complex (TC) meteoroid orbits is more structured; individual showers spanning more than three months have been identified and orbital element trends delineat-

Earth, Moon, and Planets **68**: 155-164, 1995.

ed (Štohl & Porubčan, 1990). Multiple showers arise because precession of the argument of perihelion (ω) through several cycles has resulted in the formation of multiple branches (see Babadzhanov & Obrubov, 1987). Each ω-precession cycle produces four showers: radiants north and south of the ecliptic, for both pre- and post-perihelion legs. Orbital evolution studies have shown that the timescales for the formation of the different branches observed in the TC are of order 10^4 yr (Whipple, 1940; Babadzhanov *et al.*, 1990; Steel *et al.*, 1991).

Substantial fragments of the massive progenitor may manifest themselves now as defunct (*i.e.*, asteroidal) comets. That many macroscopic objects are to be expected in the TC (Clube & Napier, 1984) has been confirmed in recent years as discoveries of near-Earth asteroids (NEAs) have progressed. About a dozen NEAs have now been identified as being members of the TC. A further alignment of objects having orbits of similar size, shape and inclination as the TC, but with a distinct longitude of perihelion (ϖ), has also been recognized, (2212) Hephaistos being the archetype (Asher *et al.*, 1994). The known short-period comets in this regard are P/Encke associated with the TC, and P/Helfenzrieder aligned with the Hephaistos group (Steel & Asher, 1994).

Štohl & Porubčan (1987) discussed the frequently used D-criterion approach to determining meteoroid stream membership, noting that a larger value of D is needed for the TC than for most streams, which are rather narrower (see Steel, 1994). The width of the observed TC implies that a range of longitudes, with varying radiants, is appropriate for each branch. Babadzhanov & Obrubov (1992) calculated shower radiants for different TC branches, including the post-perihelion (daytime) branches predicted for the observed Piscid and χ Orionid nighttime showers. The TC asteroids cover most of the longitudinal spread of the complex; in an examination of meteor data, one way to allow for the wide range of longitudes would be to look for associations with each of the individual asteroids. In principle this could also help to identify objects that are significant in feeding the meteoroid complex. Here we describe our own method for determining theoretical radiants in such a situation. We attempt to strike a balance between (i) Avoiding over-elaborate computational modelling; and (ii) Physical realism. We then compare the results with observed meteor radiants.

2 Orbit in the epoch of Earth-intercept

Obrubov (1991) demonstrated associations among various comets, asteroids and meteor showers, allowing for planetary perturbations and using a D-criterion based on the orbital elements. We note that, in essence, the calculation of a theoretical meteor radiant is a re-parametrisation of the orbital elements, given that the meteor speed and date/solar longitude are essential parts of such radiants.

Various techniques for deriving a theoretical meteor radiant from the orbital elements are reviewed by Steel (1995). The main problem to be dealt with is that the orbit of a particle producing a meteor is Earth-intersecting (*i.e.*, has a node at

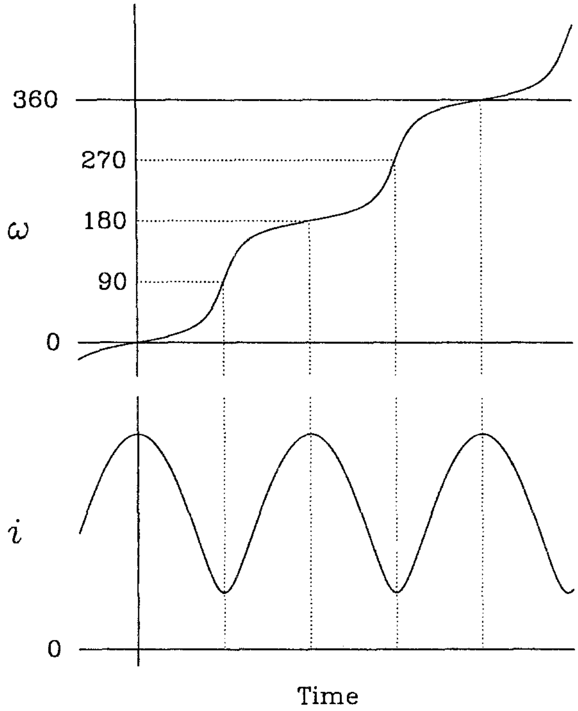

Fig. 1. Schematic diagram of i, ω precession of a typical TC orbit. Minima of i occur when ω=90° and 270°. The overall variation in i can be more than 10°.

$r = 1$ AU, a slight adaption being necessary if the Earth's eccentricity is allowed for), whereas the orbit of an asteroid that is Earth-crossing (*i.e.*, has $q < 1$ AU and $Q > 1$ AU) is not in general Earth-intersecting in the present epoch. Physically, what happens is that the particle is released from the parent, but because the ejection mechanism places it on to a slightly different orbit from that of the parent (and it may also be subject to other continuing forces, such as radiative effects), it precesses at a different rate; that rate is critically dependent upon a and e. Consequently it becomes Earth-intersecting, and therefore capable of producing a meteor, in a different epoch from the parent. In principle, the only correct way to study asteroid–meteor relationships is to generate a full model of the formation of the meteoroid stream, starting at the time of ejection. Babadzhanov & Obrubov (1987) showed how the dynamical evolution after ejection can be modelled by using the Halphen-Goryachev secular perturbation method.

Under gravitational perturbations continuing over several millennia, TC orbits maintain a and e to first order, while the angular elements i, ω and ϖ undergo major variations whose forms and cycle times depend mainly on a and e. The i- and ω-fluctuations are closely correlated (Fig. 1); there are actually similarly correlated e-fluctuations, but as these are small for TC orbits, we neglect them in this explanation. For a given a and e, the condition of Earth intersection, so that a meteor can be produced, implies just four possible values of ω (*e.g.*, Babadzhanov & Obrubov, 1987); thus a meteor-producing particle and its larger parent object will often have substantially different values of ω. Gravitational perturbations, during the time in which they are causing such differential precession in ω, will also induce substantial dispersion in i and the longitude of the ascending node Ω $(= \varpi - \omega)$.

Regarding the dynamics of the i, ω variations, we consider a simplifying assumption, avoiding precise details of differential precession resulting from differences in a and e. As ω is similar for the meteoroid and the parent object shortly after ejection, but in general quite different in the present epoch, ω obviously precesses at a different *rate* for the two orbits. However, we assume the *form* of the i and ω precession to be the same, *i.e.* that their behaviour (as shown diagrammatically in Fig. 1) is identical except for an overall compression or expansion of the time axis. Our experience in orbit studies suggests that this may be acceptable when one is aiming for broad quantitative correctness rather than perfect accuracy. The idea of our simplification is to test if a reasonable approximation for theoretical radiants can be derived effectively without allowing for further effects.

When a and e are varied, the cycle time for i and ω changes. The cycle time of ϖ also changes, but not in general by the same proportion. We could try to allow for the different changes, but in line with our attempts at producing a simplified theory, we introduce a further approximation. The two possibilities for this would be: (i) To assume that the proportional change is the same for ϖ as for i and ω; or (ii) To assume that the precession rate for ϖ is the same as for the parent. Here we choose the latter; we note that the secular period for the rotation of ϖ for TC-type orbits is ~5–10 times as long as that for ω (Asher & Clube, 1993), meaning that the error introduced by making assumption (ii) is small.

We consider, then, precession of the asteroid orbit itself. The main limitation of this idea occurs if the epoch of Earth intersection is greatly (several millennia, say) displaced from the present. Porubčan *et al.* (1992) acknowledged this problem by considering only asteroid orbits that currently approach that of the Earth to within 0.1 AU, although in reality the distance in ω-space is the important factor (with a dependence on a and e for the time needed for the appropriate amount of precession to reach a node at 1 AU). Babadzhanov & Obrubov (1984) discussed the question of not only making the orbits of meteoroid and parent match, but match in roughly the right epoch.

Regarding the evolution of the orbits, accurate backward integrations are in principle the best way to proceed. However, in the context of simplifying our derivation of theoretical radiants where possible, we should examine whether there is a simpler way. Babadzhanov & Obrubov (1987) have shown how, using an approximate integral of motion first derived by Lidov, the calculation of orbital elements at epochs of Earth intersection can be reduced to little more than solving a quadratic equation. Here we follow an approach computationally intermediate between that concept and an integration of the equations of motion, and consider secular perturbations due to Jupiter only, which has the dominant influence on TC orbits. While all available analytic secular perturbation theories for particles moving under the gravitational influence of the planets start to break down for high-e orbits, we can, using the theory of Brouwer (1947), and taking Jupiter to be in a circular orbit, find quite concise formulae for the evolution of the elements; note that we do *not* use the better known formulae of Brouwer & van Woerkom (1950), which are only applicable to lower-eccentricity orbits and have in any case been superseded by later work (see Milani & Knežević, 1994). The great advantage of our method is that after merely evaluating a few double integrals, we have simple formulae for the elements as functions of time, that are valid for all epochs (although for periods $>10^4$ yr the approximations made may render the results physically unrealistic; but they are sufficient for our purposes and very convenient).

We need to impose the condition that the particle is wholly within Jupiter's orbit, and Brouwer's derivation suggests that i in radians must be reasonably small compared to e (in fact, our numerical integration tests show that the theory works well provided $i < e/2$). These conditions are satisfied by TC orbits. Computational details, and a description of extensive tests on the theory's validity, are provided by Asher (1991); see also Asher & Clube (1993). Precession rates derived using this theory are within 10–20% of those of TC orbits in the real solar system, except near strong jovian resonances; even then, while the *rates* may be hugely affected, the *form* of the i, ω precession is closely maintained, achieving our desired result: a broadly realistic allowance for the dynamical evolution of the angular elements, the precise time taken to reach Earth-intercept being largely inconsequential. The question we are trying to answer is only 'What are the values of a, e, i, ω and Ω when Earth-intercept occurs?'

3 Results for macroscopic Taurid objects

Theoretical radiants were calculated, as discussed by Steel (1995) but using the above technique so as to deduce the orbit in the epoch of Earth-interception, for P/Encke, P/Helfenzrieder and the TC and Hephaistos group asteroids as listed by Asher *et al.* (1994). For each of the four possible branches (ω-values), the most recent value in the past 10^4 yr producing Earth intersection is plotted in Fig. 3 (nighttime radiants) or Fig. 5 (daytime radiants). The letter codes in the Figures relate to the putative parent bodies, as listed in Table I. If the full ω-precession cycle takes $> 10^4$ yr not all branches will be produced in these calculations (*e.g.*, codes C, H, P and U appear once only in Fig. 3). Observed nighttime radiants are shown in Fig. 2, for comparison with Fig. 3, and observed daytime radiants in Fig. 4, for comparison with Fig. 5. A total of 536 meteors contribute to Fig. 2, these having been selected from the radar and optical meteor orbit surveys listed by Steel *et al.* (1991), and 121 meteors contribute to Fig. 4, all but a handful of these being radar detections (the handful being a few fireballs with radiants in the sunward celestial hemisphere). The selection of these few orbits/radiants from the much larger numbers in each data set was on the basis of the radiants being within the ranges plotted in the Figures, and the orbital elements a, e and i being within limits imposed by a requirement that a difference criterion defined by

$$D^2 = (q_1 - q_2)^2 + (e_1 - e_2)^2 + \left(2\sin\frac{i_1 - i_2}{2}\right)^2$$

has a value $D < 0.15$ (see Steel *et al.*, 1991). Reference values of $q_1=0.375$ AU, $e_1=0.82$ and $i_1=4^\circ$ were used, as appropriate for the TC.

TABLE I

Letter codes for radiants plotted in Figs. 3 and 5.

Code	Object	Code	Object
	Taurid Complex:		
A	1994 AH_2	O	(2201) Oljato
B	1991 BA	P	(4341) Poseidon
C	(4183) Cuno	T	(4197) 1982 TA
E	P/Encke	U	1937 UB Hermes
G	1991 GO	V	(5731) 1988 VP_4
H	(5143) Heracles	X	1990 HA
K	1984 KB	Y	1991 TB_2
L	5025 P-L	Z	1993 KA_2
	Hephaistos group:		
a	1991 AQ	m	(4486) Mithra
c	P/Helfenzrieder	s	1990 SM
h	(2212) Hephaistos	t	1990 TG_1

There are several radiants close to the ecliptic in Figs. 3 and 5, most of which would have appeared at substantially higher ecliptic latitudes if we had not allowed for i-variations in a dynamically realistic way, since the objects have larger inclinations (and nodes far from 1 AU) in the current epoch. Close inspection shows the theoretical radiants to appear symmetric about the ecliptic but the observed ones to be roughly symmetric about a line a degree or so below the ecliptic; this is due to the jovian orbital plane being about that much below the ecliptic at those longitudes. A refinement to allow for this is possible, but here we have been more concerned with the effect of the varying inclination, such variations being much larger than the $1\overset{\circ}{.}3$ inclination of Jupiter.

Although it is the major result of this paper, few words are needed to make the point that our theoretical radiants for macroscopic objects compare very well

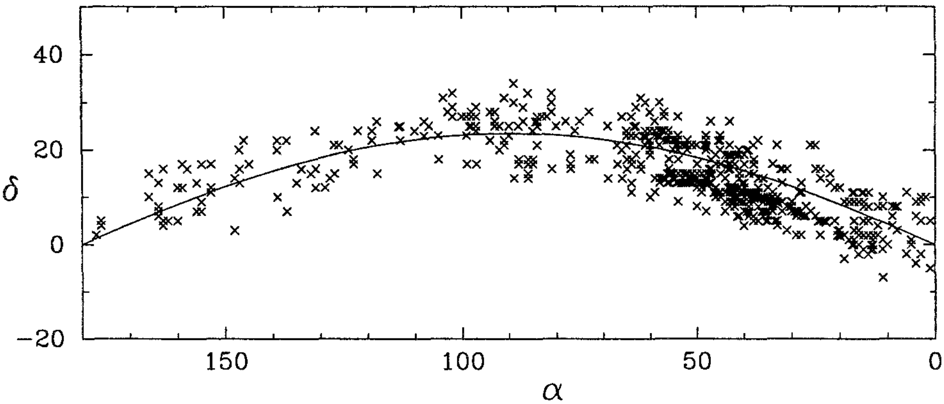

Fig. 2. Observed nighttime radiants, selected as described in the text from the optical and radar meteor orbit surveys listed by Steel *et al.* (1991). A total of 536 meteors contribute. Axes are Right Ascension (α) and Declination (δ), in degrees. The curve delineates the ecliptic. The scatter in the radiants would be increased, perhaps to match that in Fig. 3, if we either relaxed the limit on our D-criterion, or reduced the dependence upon i in the definition of that criterion.

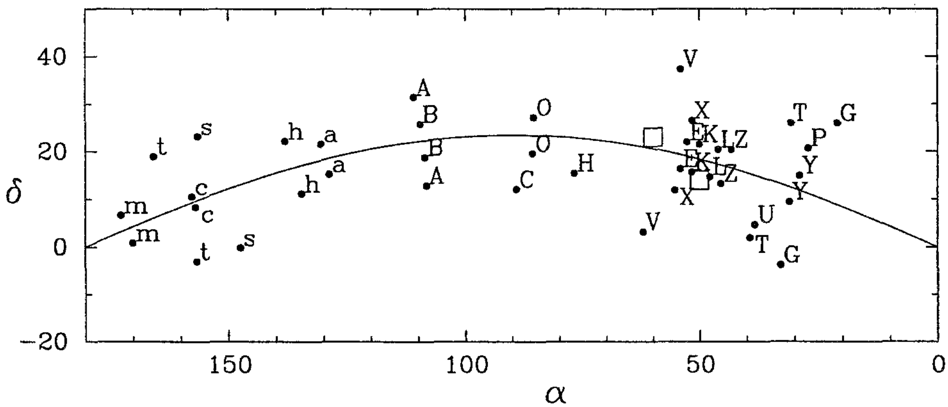

Fig. 3. Nighttime theoretical radiants. The squares are the nominal Northern and Southern Taurid radiants, from Cook (1973). The coding of the letters plotted is given in Table I.

with the observed meteor radiants both in terms of extent in α, scatter about the ecliptic, and concentrations. Fig. 3 quite closely echoes the observed distribution in Fig. 2. The theoretical radiants labelled E, K, L, Z and X in Fig. 3 may be correlated with the densest concentration south of the ecliptic in Fig. 2 (the Southern Taurids, also shown by the southern of the squares plotted in Fig. 3), although this may be an effect of the current incompleteness of NEA discoveries; it will be interesting to see what happens as more NEAs are found. Gaps in Figures 3 and 5 might also be expected to fill in as more NEAs are added to the inventory. The only real discrepancy in comparing the two pairs of Figures is in the daytime pair,

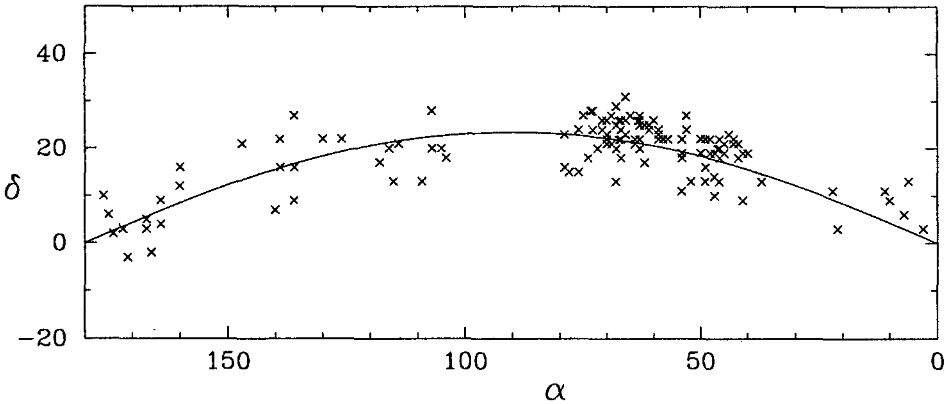

Fig. 4. Observed daytime radiants, as observed in various meteor orbit surveys and selected as described in the text. A total of 121 meteors contribute. As noted in the caption to Fig. 2, closer agreement with the declination scatter in Fig. 5 would be obtained if our constraint upon acceptable inclinations were relaxed.

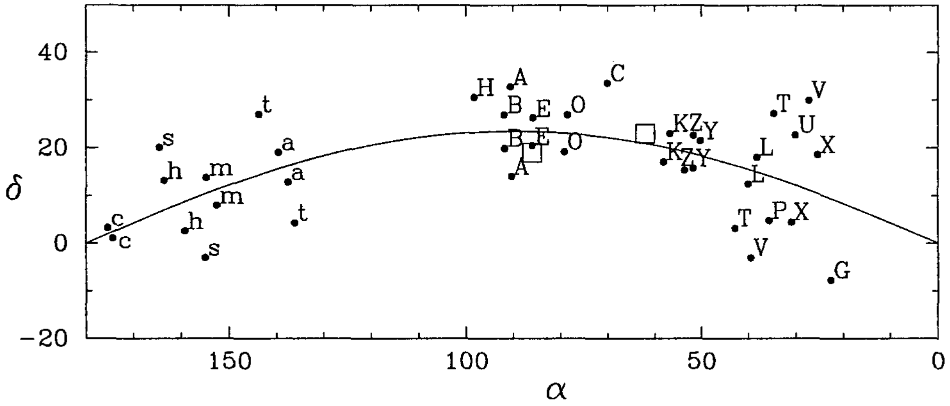

Fig. 5. Daytime theoretical radiants. The squares are the nominal β Taurid and ζ Perseid radiants, from Cook (1973); the latter radiant in particular is not well determined. Letter coding is set out in Table I.

where gaps appear at $20^\circ < \alpha < 40^\circ$ and $80^\circ < \alpha < 100^\circ$ in Fig. 4 whereas there are theoretical radiants predicted in these regions in Fig. 5. However, Fig. 4 results in the main from just three radar meteor surveys, none of which operated continuously. It appears that the gaps in Fig. 4 result from the lack of data collection at the appropriate times.

In Fig. 3 the asteroids 1994 AH_2 and 1991 BA bridge the gap between the TC core and Hephaistos group. Štohl & Porubčan (1992) associated small asteroid/large meteoroid 1991 BA with the Southern ρ Geminids, a minor shower in the extended TC. As 1994 AH_2 appears to be librating in the 3:1 mean motion resonance with Jupiter, it is still unclear whether it relates to the TC asteroids derived from a giant comet progenitor, or to the phenomenon of asteroids delivered into Earth-crossing orbits from near-resonant regions in the asteroid belt, as described by Morbidelli *et al.* (1994). In Fig. 5 there is a much clearer gap between the TC and Hephaistos groups, but more NEA orbits will be needed to confirm this.

4 Conclusions

We have presented a method of determining theoretical meteor radiants that avoids elaborate computational modelling, and the introduction of large numbers of free parameters that would bring, and yet is dynamically realistic. This method seems to reproduce the general features of the observed Taurid radiant distributions. On the one hand, this gives us confidence that our technique is a realistic representation of the orbital evolution of the particles in question which is therefore of general utility; on the other hand, the agreement for this particular application adds weight to our view that there are at least two sub-jovian complexes of meteoroids which contain significant numbers of kilometre-plus asteroids and comets, the complexes being produced by the disintegration of giant comets over periods of $\sim 10^4$ yr. It would be an improvement if the technique were made slightly more sophisticated, through an explicit consideration of ejection processes and their effects on orbital size and shape.

Acknowledgements

This work was supported by the Australian Research Council and the Department of Education, Employment and Training. We thank the referee for helpful comments which led to an improvement of this paper.

References

Asher, D.J. (1991). "The Taurid meteoroid complex." D.Phil. thesis, University of Oxford.

Asher, D.J. & Clube, S.V.M. (1993). "An extraterrestrial influence during the current glacial-interglacial." *Q. J. R. Astron. Soc.*, **34**, 481–511.

Asher, D.J., Clube, S.V.M., Napier, W.M. & Steel, D.I. (1994). "Coherent catastrophism." *Vistas Astron.*, **38**, 1–27.

Babadzhanov, P.B. & Obrubov, Yu.V. (1984). "Secular perturbations of Apollo, Amor and Aten asteroid orbits and theoretical radiants of meteor showers, probably associated with them." *Asteroids, Comets, Meteors*, eds Lagerkvist, C.-I. & Rickman, H., Uppsala University, Uppsala, pp. 411–417.

Babadzhanov, P.B. & Obrubov, Yu.V. (1987). "Evolution of meteoroid streams." *Interplanetary Matter*, eds Ceplecha, Z. & Pecina, P., Czechoslovak Academy of Sciences, Ondřejov, pp. 141–150. (= *Publ. Astron. Inst. Czechoslov. Acad. Sci.*, **67** (**2**), 141–150).

Babadzhanov, P.B. & Obrubov, Yu.V. (1992). "Evolution of short-period meteoroid streams." *Cel. Mech. Dyn. Astron.*, **54**, 111–127.

Babadzhanov, P.B., Obrubov, Yu.V. & Makhmudov, N. (1990). "Meteor streams of Comet Encke." *Sol. Sys. Res.*, **24**, 12–19. English translation. Russian original in *Astron. Vestn.*, **24**, 18–28.

Brouwer, D. (1947). "Secular variations of the elements of Encke's Comet." *Astron. J.*, **52**, 190–198.

Brouwer, D. & van Woerkom, A.J.J. (1950). "The secular variations of the orbital elements of the principal planets." *Astron. Pap. Amer. Ephem.*, **13**, 81–107.

Clube, S.V.M. (1987). "The origin of dust in the solar system." *Phil. Trans. R. Soc. Lond.*, **A 323**, 421–436.

Clube, S.V.M. & Napier, W.M. (1984). "The microstructure of terrestrial catastrophism." *Mon. Not. R. Astron. Soc.*, **211**, 953–968.

Cook, A.F. (1973). "A working list of meteor streams." *Evolutionary and Physical Properties of Meteoroids (NASA SP-319)*, eds. Hemenway, C.L., Millman, P.M. & Cook, A.F., NASA, Washington, D.C., pp. 183–191.

Kresák, Ľ. (1980). "Sources of interplanetary dust." *Solid Particles in the Solar System (IAU Symp. No. 90)*, eds Halliday, I. & McIntosh, B.A., Reidel, Dordrecht, pp. 211–222.

Milani, A. & Kneževič, Z. (1994). "Asteroid proper elements and the dynamical structure of the asteroid main belt". *Icarus*, **107**, 219–254.

Morbidelli, A., Gonczi, R., Froeschle, C. & Farinella, P. (1994). "Delivery of meteorites through the ν_6 secular resonance." *Astron. Astrophys.*, **282**, 955–979.

Obrubov, Yu.V. (1991). "Complexes of minor solar system bodies." *Sov. Astron.*, **35**, 531–537. English translation. Russian original in *Astron. Zh.*, **68**, 1063–1073.

Olsson-Steel, D. (1986). "The origin of the sporadic meteoroid component." *Mon. Not. R. Astron. Soc.*, **219**, 47–73.

Porubčan, V., Štohl, J. & Vaňa, R. (1992). "On associations of Apollo asteroids with meteor streams." *Asteroids, Comets, Meteors 1991*, eds Harris, A.W. & Bowell, E., Lunar and Planetary Institute, Houston, pp. 473–476.

Steel, D. (1994). "Meteoroid streams." *Asteroids, Comets, Meteors 1993 (IAU Symp. No. 160)*, eds Milani, A., Di Martino, M. & Cellino, A., Kluwer, Dordrecht, pp. 111–126.

Steel, D. (1995). "The association of Earth-crossing asteroids with meteoroid streams." These proceedings.

Steel, D. & Asher, D. (1994). "P/Helfenzrieder 1766 II and the Hephaistos group of Earth-crossing asteroids." *The Observatory*, **114**, 223–226.

Steel, D.I., Asher, D.J. & Clube, S.V.M. (1991). "The structure and evolution of the Taurid Complex." *Mon. Not. R. Astron. Soc.*, **251**, 632–648.

Štohl, J. (1980). "On time-dependent models of the meteoric background complex." *Solid Particles in the Solar System (IAU Symp. No. 90)*, eds Halliday, I. & McIntosh, B.A., Reidel, Dordrecht, pp. 141–144.

Štohl, J. (1984). "On the distribution of sporadic meteor orbits." *Asteroids, Comets, Meteors*, eds Lagerkvist, C.-I. & Rickman, H., Uppsala University, Uppsala, pp. 419–424.

Štohl, J. (1986). "The distribution of sporadic meteor radiants and orbits." *Asteroids, Comets, Meteors II*, eds Lagerkvist, C.-I., Lindblad, B.A., Lundstedt, H. & Rickman, H., Uppsala University, Uppsala, pp. 565–574.

Štohl, J. & Porubčan, V. (1987). "On applicability of meteor stream membership criteria." *Interplanetary Matter*, eds Ceplecha, Z. & Pecina, P., Czechoslovak Academy of Sciences, Ondřejov, pp. 163–166. (= *Publ. Astron. Inst. Czechoslov. Acad. Sci.*, **67** (**2**), 163–166).

Štohl, J. & Porubčan, V. (1990). "Structure of the Taurid meteor complex." *Asteroids, Comets, Meteors III*, eds Lagerkvist, C.-I., Rickman, H., Lindblad, B.A. & Lindgren, M., Uppsala University, Uppsala, pp. 571–574.

Štohl, J. & Porubčan, V. (1992). "Dynamical aspects of the Taurid meteor complex." *Chaos, Resonance and Collective Dynamical Phenomena in the Solar System (IAU Symp. No. 152)*, ed. Ferraz-Mello, S., Kluwer, Dordrecht, pp. 315–324.

Whipple, F.L. (1940). "Photographic meteor studies. III. The Taurid shower." *Proc. Amer. Phil. Soc.*, **83**, 711–745.

Whipple, F.L. (1967). "On maintaining the meteoritic complex." *The Zodiacal Light and the Interplanetary Medium (NASA SP-150)*, ed. Weinberg, J.L., NASA, Washington, D.C., pp. 409–426.