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Taurid resonant-swarm encounters from two decades of visual observations

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ABSTRACT

Enhanced Taurid activity in terms of visual meteor and fireball rates has been found in 1988, 1991, 1995, 1998 and 2005 data. The years of heightened activity are shown to be unequivocally linked to the encounters of swarms of resonantly trapped particles in the Taurid meteoroid stream according to the model proposed by Asher & Clube. While the annual activity level of the Taurid meteor shower in terms of zenithal hourly rate (ZHR) is 7.8 ± 1.2, swarm year activity typically reaches ZHRs of 12–17. The annual fraction of fireballs is below 1 per cent; in swarm years, this fraction is as high as 2.4–4.6 per cent near the maximum of the Taurid activity period.

Key words: meteors, meteoroids.

1 INTRODUCTION

The Taurid Complex constitutes a dynamical meteoroid stream composed of asteroid-sized objects to dust-sized particles that pass in close proximity to the Earth's orbit. Among them, the largest known object is Comet 2P/Encke, for more than half a century recognized as a parent object of the Taurid meteor shower (Whipple 1940). Thanks to continuously running and successful space research programmes, numerous near-Earth objects with increasing numbers of smaller, meteoroid-sized bodies have been discovered during the past few decades. Significant numbers of newly discovered near-Earth (Apollo type) or Earth-crossing asteroids have been proved to belong to the Taurid Complex (Olsson-Steel 1987; Asher, Clube & Steel 1993; Klačka 1995; Klačka & Pittich 1998; Babadzhanov 2001; Porubčan, Kornoš & Williams 2006). Such an extended membership of large objects in the stream has produced some real foundations for the hypothesis of the disintegrated giant comet (Clube & Napier 1984). The passage of the Earth through the Taurid meteor stream has been marked by bright fireballs and eventual meteorite falls (Steel, Asher & Clube 1991), by lunar impacts (Dorman et al. 1978; Cooke, Suggs & Swift 2006), and very likely by much more hazardous events in the past like the Tunguska explosion (Asher & Steel 1998), and hence continuously attracts much interest from professional and amateur meteor astronomers.

The Taurid meteoroid stream produces a well-known annual Taurid meteor shower which is active during the months of October and November with a maximum extending through the first 10 days of November. Historical records from Eastern Asia suggest that the Taurids produced a prominent meteor shower in the past (Hasegawa 1992; Ahn 2003), although the available sources do not provide a reliable distinction between the Taurids and other major meteor showers, e.g. the Leonids and the Orionids. At present, the activity of the Taurid meteor shower is rather modest and does not exceed 10 meteors at maximum in terms of the zenithal hourly rate (ZHR) (Hughes 1990; Bone 1991; Jenniskens 1994; Rendtel, Arlt & McBeath 1995), with a most typical figure of ZHR = 7–8, which is comparable to the activity of the sporadic background.

Asher & Clube (1993) proposed a dynamic model of the Taurid meteoroid stream that implies the existence of resonantly trapped particles within the stream, called a meteoroid swarm, which is formed over a time-scale of a thousand years as a consequence of the 7:2 mean motion resonance of Comet 2P/Encke with Jupiter. In the 'swarm model', enhanced Taurid activity, in particular increased fireball numbers, has been predicted, related to the resonant part of the stream. A direct comparison of the model predictions with observations by the Nippon Meteor Society over six decades by Asher & Izumi (1998) was indeed successful in finding a correlation, at least for increased fireball rates in 1988, 1991 and 1995. Independent reports on enhanced Taurid fireball activity in 1988 were based on photographic (Evans 1993) and visual (McBeath 1998) records from the British Astronomical Association and the International Meteor Organization (IMO), respectively. More recently, an extended analysis of the Taurid fireball activity from six independent surveys that covered a 40-year interval (from 1962 to 2002) revealed fireball peaks in line with resonant-swarm encounters proposed by the swarm model (Beech, Hargrove & Brown 2004).

On the other hand, the question of whether the Taurid meteor shower produces enhanced activity of meteors in the visual range during swarm years is still open. Only the observations of the Taurid meteor shower in 2005, the most recent year of the predicted resonant-swarm encounter, indeed revealed heightened visual rates (Dubietis & Arlt 2006). Therefore the aim of this paper is to verify if there exists a connection between the Taurid 'swarm encounters'

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and enhanced visual Taurid meteor activity. For this purpose we carried out a comprehensive analysis of the Taurid meteor shower over a 20-year period (1985–2005) based on the available records collected in the Visual Meteor Data Base (VMDB), which captures five predicted Taurid swarm encounters in 1988, 1991, 1995, 1998 and 2005. Our results show that for the predicted swarm years a direct correlation between the increased visual rates and enhanced fireball activity can be detected.

2 OBSERVATIONAL DATA

Visual (naked-eye) meteor observations allow for a quantitative evaluation of the meteor activity including stream parameters such as the flux density and the mass index. The VMDB maintained by the IMO comprises the most comprehensive data set of standardized visual observations ever accumulated by the joint efforts of amateur meteor observers around the globe. With data going back to 1984, the VMDB provides year-round observational records for more than 50 distinct (major, minor and periodic) meteor showers related to known bodies of the Solar system, sporadic meteor activity and individual meteor magnitudes. The Taurid activity is well reflected there, and the records of 1985–2005 contain more than 33 000 Taurid meteors and their magnitudes which are readily available for the analysis. Table 1 gives the Taurid numbers available for each of the years from 1985 to 2005.

From long-term photographic and visual observations in the past, the Taurid meteor shower has been designated a twin radiant structure with clear northern and southern branches that developed under large-time-scale planetary perturbations on the meteoroid stream with low orbital inclination (Jones 1986). Numerous theoretical radiants, mostly related to the asteroidal counterpart of the stream, had been predicted (Asher & Steel 1995; Babadzhanov 2001). A recent study of photographic orbits in the International Astronomical Union (IAU) meteor data base found possible associations between the Taurid substreams (filaments) and nine near-Earth objects (Porubčan Kornoš & Williams 2006). On the other hand, the analysis of about 58 000 video meteors by Triglav-Čekada & Arlt (2005) revealed just a wide double radiant of the Taurids, with clearly separated northern and southern branches (referred to as Northern and Southern Taurids, respectively). In the present analysis, we have adopted a mean Taurid radiant position of $\alpha = 52^\circ$ and $\delta = +17^\circ$ (for November 5, $\lambda_\odot = 222^\circ$) with an averaged daily drift of $\Delta\alpha = +0\overset{\circ}{.}82$ and $\Delta\delta = +0\overset{\circ}{.}18$. This simplified ephemeris is based on the radiant positions recently derived by Triglav-Čekada & Arlt (2005).

Table 1. Observational data for the Taurids between 1985 and 2005. The numbers of northern Taurids (NTAs), southern Taurids (STAs) and undiscriminated Taurids (TAUs) are given. For the analysis, however, only the total of the three columns is used. Additionally, the date of full Moon closest to the Taurid activity maxima is given. The worst coincidences are marked with '!'.

Year	NTAs	STAs	TAUs	Total	Full Moon
1985			250	250	Oct 28
1986		72	342	414	Nov 16
1987	12	132	211	355	Nov 05
1988	472	784	980	2236	Oct 24
1989	387	433	413	1213	Nov 12
1990	762	798	412	1972	Nov 02
1991	667	637	271	1575	Nov 21
1992	326	252	381	959	Nov 10
1993	328	266	362	956	Oct 30
1994	425	341	237	1003	Nov 18
1995	1102	1069	505	2676	Nov 07 !
1996	769	617	572	1958	Oct 26
1997	769	619	200	1588	Nov 14
1998	1864	1397	1887	5148	Nov 08 !
1999	1279	1053	1921	4253	Oct 24
2000	371	357	638	1366	Nov 11
2001	804	611	1225	2640	Nov 01
2002	163	169	276	608	Nov 19
2003	77	69	359	505	Nov 08 !
2004	125	98	297	520	Oct 27
2005	481	499	392	1372	Nov 15

The activity period of the Taurid meteor shower extends over two months, from September 25 to November 25 (Rendtel et al. 1995); the long duration resulting from the low orbital inclination of the meteoroid stream. Northern and Southern branches of the shower produce quite similar activity, with individual maxima on November 5 and 10, respectively. This creates the appearance of a broad overall maximum centred at November 7. It is worth mentioning that sufficient coverage of such an extended activity period requires a large number of observational data, which is usually achieved by combining the observations from different years. This method may be acceptable for the derivation of the average activity profiles; however, it washes out many important details of the annual behaviour of the shower. This is the main reason why the visual Taurid analyses performed so far have not been capable of capturing increased Taurid activity in particular years. In the present analysis, we derive the individual activity profiles for each year, taking special care for the years of interest (1988, 1991, 1995, 1998 and 2005). For the sake of simplicity, we made no distinction between the Northern and Southern branches, and refer to the shower as the Taurids henceforth.

3 DATA ANALYSIS

A commonly accepted procedure in evaluating visual meteor activity produced by a particular meteor shower involves the calculation of the ZHR, which is the hourly rate of meteors seen by a single observer under optimum sky conditions, which are quantitatively described by a stellar limiting magnitude of $L_\mathrm{m} = +6.5$, and with the radiant being situated in the local zenith. The ZHR is computed as

$$\mathrm{ZHR} = \frac{N r^{6.5 - L_\mathrm{m}} F}{T_\mathrm{eff} c_\mathrm{p} \sin^\gamma h_\mathrm{R}}, \tag{1}$$

where N is the number of shower meteors observed in a time interval T_eff, L_m is the limiting stellar magnitude, F is the correction for the field obstruction (cloud coverage, etc.), r is the population index of the shower meteor magnitude distribution, h_R is the radiant elevation, γ is the zenithal exponent (for non-sinusoidal radiant elevation correction) and c_p is the individual perception correction. The typical diameter of the field of view of a visual observer is about 100°. The field obstruction factor F refers to this field, not to the entire sky.

All of the parameters in the above equation may be known by the time the observation is made, except for the population index r which depends on shower and time. It is an important characteristic of the particular meteor shower and is linked to the mass index of the related meteoroid stream. Ideally, the population index has to be computed as a function of time before any ZHR computation is done. It is generally expressed as $r = n(m+1)/n(m)$, where $n(m)$ is the number of observed meteors $N(m)$ of a given magnitude m corrected by the detection probability $p(m)$ and assumes the exponential growth of the true number of shower meteors towards fainter magnitudes. Average detection probabilities were derived by Koschack & Rendtel (1990) and led to a direct conversion method of the average differences $L_\mathrm{m} - m$ of the meteors into r. More details on the method and conversion tables are given by Arlt (2003). In our case, a single value of the population index of the Taurids was computed for each year and was used for the ZHR computations of that specific year. Since the variation of the population index during the activity period of each year requires very large data sets, we ignored the time dependence within the activity period.

The correction factor for the cloud cover F is computed as $F = 1/(1-k)$, where k is the average part of the field of view covered by clouds during the observing period T_eff. The zenithal exponent γ applies as a correction for the dependence of meteor brightness on its entry angle into the atmosphere. Bellot Rubio (1995) showed that for naked-eye observations $\gamma \simeq 1$, although the full nature of the dependence has still not been explored. In the present analysis, only the geometrical correction as $1/\sin h_\mathrm{R}$ is used, which is a good approximation for radiant elevations h_R above 10°. In the case of multiple observations, the perception of an individual observer is reduced to unity ($c_\mathrm{p} = 1$); the ZHR is thus expressed as

$$\mathrm{ZHR} = \sum_i N_i \Bigg/ \sum_i \frac{T_{\mathrm{eff},i}}{C_i}, \tag{2}$$

where

$$C_i = \frac{r^{6.5-L_{\mathrm{m}i}} F_i}{\sin(h_{\mathrm{R},i})} \tag{3}$$

is the total correction factor for the limiting magnitude, field obstruction and radiant elevation. The index i refers to the individual observing periods. The total correction C_i then readily serves for the data reduction. In our calculations we have used $C_i \leqslant 5$, which ensures that only quality observations are used for ZHR calculations: the upper limit of $C_i = 5$ establishes a minimum radiant elevation for acceptable observations $h_\mathrm{R} > 10°$ with $L_\mathrm{m} = 6.5$ and so on, and practically ensures that observations under poor sky conditions or unfavourable geometric conditions are not taken into account. The error margins of the calculated ZHR values are estimated as

$$\Delta\mathrm{ZHR} = \mathrm{ZHR} \Bigg/ \sqrt{\sum_i N_i}. \tag{4}$$

ΔZHR is the statistical error in the meteor counts, which obey Poissonian statistics to a very high degree. The ZHR and the population index r can then be converted into physical parameters of the meteoroid stream – the mass index and the spatial number density of particles.

4 RESULTS AND DISCUSSION

We first analysed the activity of the Taurid meteor shower in 1985–2005 by deriving the individual ZHR profiles (not shown here) for each year, using a 1° step in solar longitude, which corresponds to approximately 1-d periods. Of course, such a step does not allow the fine details of the shower activity to be retrieved; it is, however, as will be shown later, sufficient for building an activity profile and hence permits a plausible characterization of the overall activity level. For each of the individual profiles, a peak ZHR (denoted as $\mathrm{ZHR}_\mathrm{max}$) was evaluated, and we ascertained that its time falls into the period of an extended Taurid maximum ($\lambda_\odot = 220°$ to 230°).

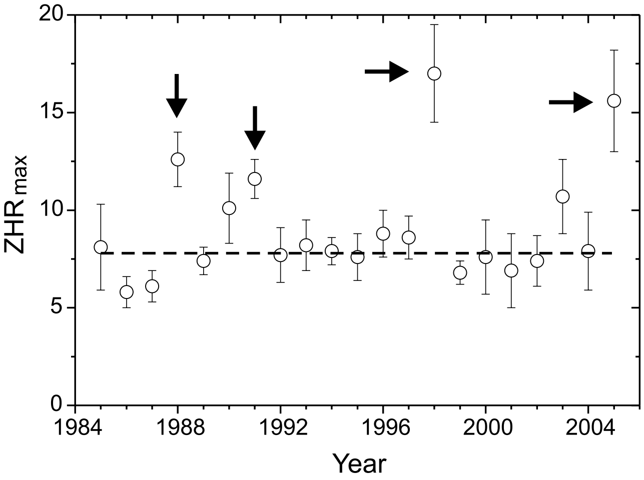

Figure 1. Summary of the Taurid meteor shower activity in 1985–2005. Years of enhanced activity coincide with the swarm years of the Taurid meteoroid stream and are indicated by arrows. The annual average is shown by a dashed line.

The results are summarized in Fig. 1. Two important conclusions follow immediately from the plot.

(i) The annual Taurid rates in non-swarm years do not vary significantly from year to year and fall into the $\mathrm{ZHR}_\mathrm{max}$ interval of 6–10, with an average value ZHR = 7.8 ± 1.2 (shown by a dashed line). Our results are consistent with those given in the literature and obtained using independent data sets (Hughes 1990; Bone 1991; Jenniskens 1994; Rendtel et al. 1995), unless the latter had been derived by averaging over a few years at least.

(ii) There are four prominent peaks with an increase in visual Taurid rates to about twice the annual $\mathrm{ZHR}_\mathrm{max}$ in 1988, 1991, 1998 and 2005. This finding readily suggests a link to the encounters with Taurid resonant swarms, exactly as predicted by the model. The results reveal a correlation between visual-range activity and the Taurid stream swarms which has not been shown hitherto.

It is worth mentioning that the overall success of the analysis of visual observations greatly depends on the sky conditions and, of course, on the number of observations available for averaging. The available quality observations were notably reduced by the full Moon coinciding with the Taurid maxima in 1995 and 1998. Limiting magnitudes are lowered by at least half a magnitude then, and fewer observers are out for activity monitoring. Interestingly, these are the two years with the largest (1998) and the third-largest (1995) numbers of Taurids that were available to the analysis (Table 1). A considerable fraction of the 1998 Taurids was observed during the activity period of the Leonid meteor shower.

The individual Taurid activity profiles are plotted in Fig. 2 in detail. The profiles illustrate the four relevant cases of enhanced Taurid activity in 1988, 1991, 1998 and 2005, which coincide with the encounters with Taurid resonant particles predicted by the swarm model. The individual profile of 1995 is not shown, since its quality was severely limited by bad observing conditions resulting in much poorer observational data. The annual activity profile, which was derived by combining the observations during the non-swarm years in the period 1985–2004 and comprises a total set of more than 18 000 shower meteors, is added for a comparison. Note that because of averaging and uncertainty in maximum position, the annual profile gives a somewhat lower activity level than that depicted in Fig. 1 and therefore rather serves more as a guide for the eye.

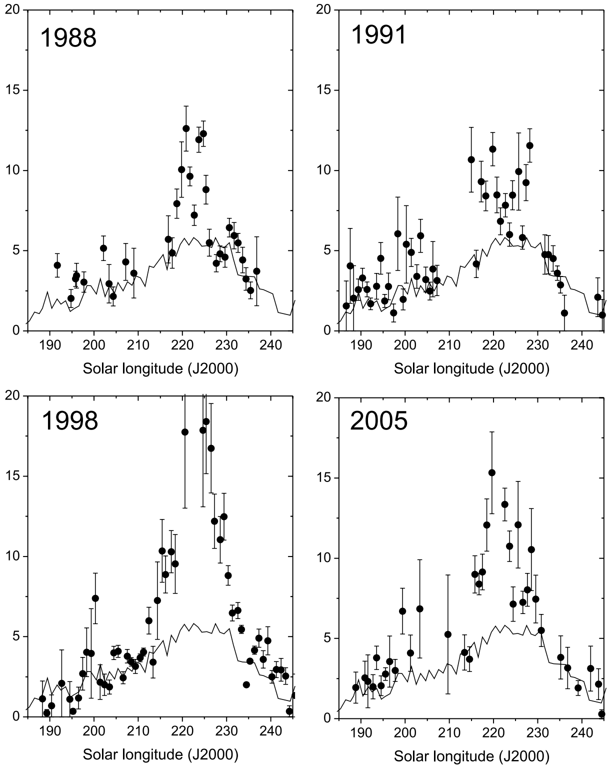

Figure 2. Activity profiles of the Taurid meteor shower for the years of resonant encounters. A typical annual profile is added for comparison and is shown by a solid line.

Concerning the appearance of bright Taurid fireballs, a reliable connection between the enhanced fireball rates and resonant stream encounters has already been established, and there exists a widespread opinion that the Taurid meteor shower, despite its moderate activity, produces a high proportion of fireballs. Bone (1991) analysed the Taurid activity in 1981–88 and cast doubt on that fact, since he found that the fireball proportion in the Taurid meteor shower is not much different from that provided by the sporadic meteor activity. However, a more thorough analysis, carried out by Evans (1993) on photographic data and by McBeath (1998) on visual meteor data, has revealed that a significant fraction of Taurid fireballs occurred in 1988, 1991 and 1995. An extended analysis of six fireball surveys over a 40-year period (1962–2002) revealed a perfect correlation between enhanced fireball rates and the swarm model predictions (Beech et al. 2004). Therefore we found it reasonable to cross-check how the visual Taurid activity correlates with available fireball records collected in the VMDB. Typically, meteors of magnitude -3 and brighter are termed fireballs. Verniani (1973) and Hughes (1987) provided an empirical relation between the absolute meteor magnitude, its mass and its atmospheric entry velocity. According to this relation and assuming an average atmospheric entry velocity of 28 km s^{-1} for Taurid meteors, a Taurid fireball of magnitude -3 is produced by a meteoroid with a mass of $\sim$15 g.

The VMDB contains a total of 25 264 Taurid magnitudes reported throughout the months of October and November in the years 1987–2005, which include 350 reports on fireballs of magnitude -3 and brighter. To proceed with fireball data analysis, we first estimated an average fireball proportion for the non-swarm years, excluding the reports of the probable swarm years 1988, 1991, 1995, 1998 and 2005. The data set was thus reduced to 15 228 individual magnitude estimates with 166 fireballs. A simple evaluation of the ratio of number of fireballs to total number of meteors, $N_{\mathrm{f}}/N_{\mathrm{met}}$ resulted in an average fireball proportion of 1.09 per cent for the non-swarm Taurids, a number that is very similar to that of the other major meteor showers, the Perseids and the Geminids (McBeath 1998). The remaining 184 fireballs were observed during 1988, 1991, 1995, 1998 and 2005 and yielded a considerably higher average fireball proportion of 1.83 per cent. In order to ascertain that the obtained higher fireball proportion is not a result of a single specific year, we further derived the Taurid fireball proportion for each individual year. The results are plotted in the lower panel of Fig. 3. The upper panel shows the population index which was also computed for each individual year, and which was used for the computation of the ZHR profiles of the corresponding years.

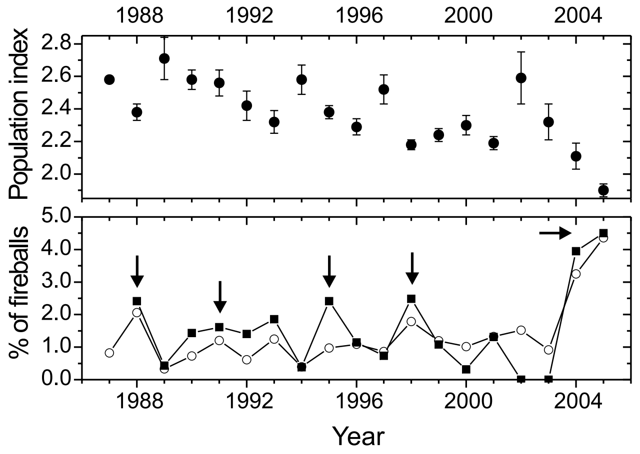

Figure 3. Variations of the population index (top panel) and the proportion of fireballs (bottom panel) in the Taurid meteor shower versus year from visual observations. In the bottom panel, arrows denote the years of resonant encounters; open circles denote the fireball proportion over the entire Taurid activity period; while full squares denote the fireball proportion over a reduced period around the shower maximum.

We see three clear peaks in the fireball proportions in Fig. 3, indicating increased fireball rates during the resonant Taurid encounters in 1988, 1998 and 2005. In contrast, no clear evidence for increased fireball rates in 1991 and 1995 is found. The recalculation of the fireball proportion within a shorter period of time close to the shower maximum ($\lambda_{\odot} = 215°$–$235°$) eventually reveals a peak in 1995, whereas it does not affect the result for 1991. However, fireball activity peaks do not affect the general trend of the population index, which scatters around the average value of $r = 2.4$ and shows no apparent trend. The slope of the logarithmic true meteor numbers is chiefly determined by the meteors in the visual range of magnitudes 0 to $+5$ and not by the comparatively low number of fireballs. A population index derived from the fireball magnitude range must be quite different from the visual-range r. The number of fireballs does not permit a computation of a reliable fireball r, however. As we did for the fireball fractions, we also restricted the Taurid magnitude sample to the period $\lambda_{\odot} = 215°$–$235°$ and computed the population indices for each year. There is little significant difference from the population indices derived for the entire activity period. The strongest exception is the 1995 value which drops significantly to $r = 2.0$ and may thus indicate a swarm year.

The main results are summarized in Table 2. The investigated period captured five of the predicted Taurid resonant encounters. High visual rates were detected in 1988, 1998 and 2005, whereas the enhancement in 1991 was weaker, but still significant. In 1995,

Table 2. Comparison of visual rates (peak ZHR) and fireball activity (normalized by the number of observed meteors, N_f/N_{met}) of the Taurid meteor shower in 'swarm years'. ΔM is the mean anomaly displacement of the resonance centre from the point at which the swarm orbit crosses the orbit of the Earth, given by Asher & Clube (1993).

Year	ΔM	Peak ZHR	N_f/N_{met} $\lambda_\odot = 185°–250°$	N_f/N_{met} $\lambda_\odot = 215°–235°$
1988	$+5°$	12.6 ± 1.4	2.06	2.42
1991	$-36°$	11.6 ± 1.0	1.21	1.61
1995	$+29°$	7.6 ± 1.2	0.97	2.42
1998	$-13°$	17.0 ± 2.5	1.79	2.48
2005	$+11°$	15.6 ± 2.6	4.40	4.56
Annual	–	7.8 ± 1.2	1.09	0.98

the Taurid activity was just at the level of the annual average, and this result can partly be attributed to poor observing conditions imposed by the full Moon. The general result can be understood with reference to the encounter conditions (ΔM), which imply best rates for the encounters in 1988, 1998 and 2005. The evaluated fireball proportions suggest that four of the five predicted swarm encounters resulted in enhanced fireball rates as well. No enhanced fireball rates were apparently captured by VMDB records for 1991. However, complementary information available from other, independent sources (McBeath 1998; Beech et al. 2004) is likely to confirm enhanced fireball rates for 1991 as well.

5 CONCLUSIONS

Relying upon the outcomes of the most comprehensive data set of standardized visual observations accumulated in the VMDB, we have revealed a straightforward link between the Taurid swarm encounters and enhanced visual meteor rates exhibited by the shower. Our finding is supported by an analysis of the Taurid activity in terms of visual meteor rates and fireball proportions over a 20-year period. The results outline an apparent correlation of the activity of visual meteors and the fireball abundances with the mean-anomaly difference of the centre of a resonant swarm in the Taurid stream from the Earth-crossing location. The observed activity enhancement in visual rates allows us to quantify the strength of the swarm encounters. An exact relationship between the encounter conditions and visual meteor rates has still to be established, though.

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