DECOHERENCE TIME SCALES FOR 'METEOROID STREAMS'

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Abstract

We explore the orbital dynamics of an Earth-crossing objects with the intent to understand the time scales under which an 'orbital stream' of material could produce time-correlated meteororite falls. These 'meteorite streams' have been suggested to be associated with three well-known meteorite-dropping fireballs (Innisfree, Peekskill, and most recently Príbram). We have performed two different analyses of the statistical significance of the 'orbital similarity', in particular calculating how often orbits of the same level of similarity would come from a random sample. Secondly, we have performed extremely detailed numerical integrations related to these three cases, and find that if they were streams of objects in similar orbits then they would become 'decoherent' (in the sense that the day of fall of meteorites of these streams become almost random) on times scales of a few tens of thousands to a few hundred thousand years. Thus, an extremely recent breakup would be required, much more recent that the cosmic ray exposure ages of the recovered falls in each case. We conclude that orbital destruction is too efficient to allow the existence of long-lived meteoroid streams and that the statistical evidence for such streams is insufficient; random fall patterns show comparable levels of clustering.

1 Introduction

Meteor streams are a well-accepted and well-understood phenomenom, in which an object of cometary composition loses material during each orbit and populates a region of orbital space near that of the parent comet with small particles that have escaped from the comet at low speeds; if this orbit is currently intersecting Earth's we see an annual meteor shower near the day of the nodal intersection. Due to the recent and continual re-supply caused by the perihelion passage, many meteors on very similar pre-atmospheric orbits occur due to the entry of particles recently escaping from the parent comet and occupying nearly the same orbit (*eg.* Messenger, 2002).

The situation is much more unclear regarding meteorite-dropping fireballs, that is, fireballs for which the pre-atmospheric object is sufficiently large and strong to survive atmospheric entry and deliver intact fragments to the ground. Some fireballs have been observed by photographic camera networks (Halliday *et al.* (1978), McCrosky *et al.* (1979), Ceplecha (1977)) or by ground-based observers (*eg.* Brown *et al.* , 1994) with sufficient coverage to compute a pre-atmospheric orbit for the incoming object, some fraction of which will be non-cometary. Wetherill and Revelle (1981) and Halliday *et al* (1996) analyzed photometric fireball data from the Prairie and MORP networks to filter out fireballs whose pre-atmospheric objects were likely cometary. Morbidelli and Gladman (1998) showed that the orbital distribution of the non-cometary fireballs (presumably mostly chondritic) was perfectly consistent with sources in the main asteroid belt, as is commonly accepted.

The fireball orbit database has been analysed by several workers to search for the possibility of 'meteoroid streams'; that is, meteorite dropping fireballs whose pre-atmospheric orbits would indicate that there is a stream of meteoroids in very similar Earth-crossing orbits. We summarize below the three main cases, which we will later use as case studies for our detailed numerical integrations. The orbits are listend in Table 1.

Príbram: One of the largest fireballs with a well-determined orbit is that of Príbram, an H5 ordinary chondrite which was observed by the European Camera Network on April 7 1959 (Ceplacha 1977). On April 6 2002 the Neuschwanstein chondrite (Spurný *et al.* 2003) was also observed by the same camera network and calculated to have a very similar orbit to that of Príbram. They estimate that, based on 200 'meteor candidate' orbits taken from the MORP data, the probability of getting a orbital match as close as that observed was 1 in 100,000 and that therefore the Príbram/Neuschwanstein similarity was not chance, although reconciling the different petrographic types (H5/EL6, respectively) and very different cosmic-ray exposure ages (CRE) (12/48 Myr, respectively) was acknowledged to be problematic.

Innisfree: The Canadian Meteorite Observation and Recovery Project (MORP) observed a fireball on Feb 5, 1977 (Halliday *et al.* 1978), and subsequently recovered the Innisfree LL-chondrite fragment. Three years later the same network observed a second fireball (Halliday *et al.* 1987) which should have resulted in a fall near Ridgedale

Fall	a(AU)	e	i	Ω	ω	q (AU)
Príbram	2.401	0.6711	10.482°	17.79147°	241.750°	0.7895
Innisfree	1.872	0.473	12.27°	316.80°	177.97°	0.986
Peekskill	1.49	0.41	4.9°	17.030°	308°	0.88

Table 1: Pre-atmospheric orbits of three fireballs of interest. Data are taken from Spurný *et al.* (2003), Halliday *et al.* (1987) and Brown *et al.* (1994). Here a is the semi-major axis; e is the eccentricity; i is the inclination; Ω is the longitude of ascending node; ω is the argument of pericenter; and q is the perihelion distance. Table 2 lists the companion fireballs for Príbram and and Innisfree. The last digit in each measurement is uncertain.

Saskatchewan (and is thus known as Ridgedale even though no material was recovered). The calculated pre-atmospheric orbits of these two objects were quite similar, leading Halliday *et al.* (1987) to postulate the existence of a meteoroid stream. They noted that the 27-Myr CRE age was problematic in terms of the size expected for the parent object; that is, a parent object larger than 140 m diameter would have to be fragmented in order to get two fireballs, and yet the CRE data shows that Innisfree itself was either in a $<$4 m body when it hit the atmosphere or spent most of its CRE exposure on the surface of a 140-meter object (a problem we shall address in our conclusions). Those authors did note that the light production and fragmentation pattern of Ridgedale was quite different from that of Innisfree; they ascribed this to Innisfree having more fractures before hitting the Earth's atmosphere. In a final paper, Halliday *et al.* (1990) examined the MORP and Prairie network (McCrosky *et al.* 1979) databases and selected several fireball groups as potentially corresponding to streams of meteoroids in Earth-crossing orbits; Innisfree/Ridgedale are part of the most significant grouping that they find, and that grouping was also proposed to be linked to a stream of asteroids by Drummond (1991).

Peekskill: The last meteoroid stream candidate we will explore is one lacking direct observation of two similar pre-atmospheric orbits. Rather, Dodd *et al.* (1993) identified a set of meteorites which had similar day of fall parameters and sets of labile trace elements, as determined by a multivariate statistical analysis, and proposed meteoroid streams as a mechanism to explain the pattern. Later, these same authors (Lipschutz *et al.* , 1997) noted that the well-observed Peekskill fall (Brown *et al.* 1994) was part of one of their identified streams. Thus, although close orbital similarity with another fireball does not exist here, we will also study the orbital evolution of a 'Peekskill' stream.

Our approach to the problem will be to first attempt to calculate the statistical significance of the level of 'similarity' that has been observed in the growing world-wide database of fireball orbits. We will do this by examining the number of cases of similarity that one would find from a totally random distribution of Earth-impacting objects. We will then proceed to perform numerical integrations of the three stream candidates discussed above

Object	Original Fall	a(AU)	e	i	Ω	ω	D'
Neuschwanstein	Príbram	2.40	0.67	11.41°	16.82664°	241.20°	0.009
Ridgedale	Innisfree	1.873	0.475	12.33°	316.01°	186.66°	0.034

Table 2: Pre-atmospheric orbits of companion fireballs. These objects have very similar orbits to the original fall in each case (as listed in Table 1). Data are taken from Spurný *et al.* (2003) and Halliday *et al.* (1987). The last digit in each measurement is uncertain.

to measure the time scale over which such material could retain a 'stream-like' characteristic.

2 Statistical significance of orbital similarity

The introduction identified three main arguments for the existence of 'streams' of meteoroids: (i) The existence of pairs fireballs with *very* similar pre-atmospheric orbits; (ii) The existence of 'clusters' of fireballs with mutually similar orbits; and (iii) The existence of meteorite falls with correlated day-of-fall and chemical trace elements. In this section, we wish to examine the statistical strength of these claims. That is, we wish to determine the rate of chance coincidences occurring in 'random' distributions of meteorite falls. To conclude that such a signal is non-random, we would normally wish that such occurences fall outside a one-sided 3σ deviation; that is, the clustering happens less than (100-99.7)/2= 0.15% of the time. (Obviously no-one would get excited if the clustering was 3σ *less* than a random distribution!). However we shall see that even one-sided 2σ deviations (which occur less than 2.5% of the time in a random distribution) are rare.

In Sections 2.2 and 2.3, we repeat calculations performed in several papers in the literature in support of arguments (i) and (ii) on 'random' fireball databases. The generation of our 'random' databases are described in Section 2.1. Argument (iii) is more complicated to model, and we thus examine this argument only in the context of our dynamic modelling of streams in Section 3.

2.1 Modelling a 'Random' Distribution of Fireballs

In order to assess the probability of chance coincidences from a 'random' fireball distribution, we created two 'unclustered' fireball databases: one based on our current theoretical understanding of the source of meteoritic fireballs (*i.e.,* the Near-Earth Asteroid (NEA) population), and one based on the current database of real fireball orbits. In both cases, our goal is to build an orbital distribution of fireballs which, while having an (a, e, i) distribution similar to real fireballs has no correlations in the other angular orbital variables which would produce pre-atmospheric orbital similarities.

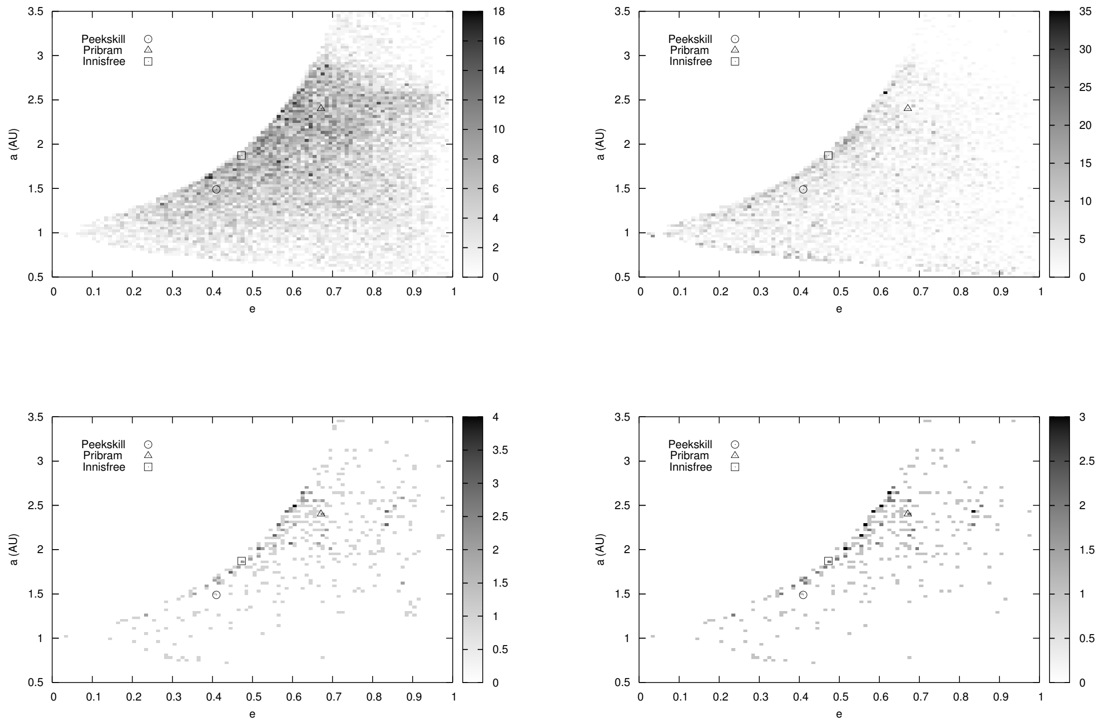

Figure 1: Greyscale histograms of our various fireball databases in $a-e$ space. The greyscale indicates the relative population in each $a-e$ cell. In all panels, the elements of the three stream candidates are also indicated. (**Upper left**): Our raw sample of the NEA modelling of Bottke *et al.* (2002), restricted to lie with pericenter below 1 AU and apocenter above 1 AU. (**Upper right**): A sample generation of 10000 Earth-impacting fireballs from the NEA model biased by the collision probability of Fig. 2. (**Lower left**): The database of 481 Type I and II fireballs; (**Lower right**): The restricted database of 351 Type I and II fireballs obtained by selecting orbits from the 481 Type I and II fireballs with terminal masses greater than 100 grams and encounter velocities below 25 km/s (Section 2.3). Similar selection criteria were applied by Halliday *et al.* (1990). Note that the collision probability bias heavily selects particles along the fringes of the distribution (corresponding to perihelion and aphelion near 1 AU), and thus greatly reduces the variety of Earth-impacting orbits. Note also the effect of restricting our fireball database to low encounter velocities: orbits with high eccentricity are removed, further reducing the range of the orbital elements of Earth-impacting orbits.

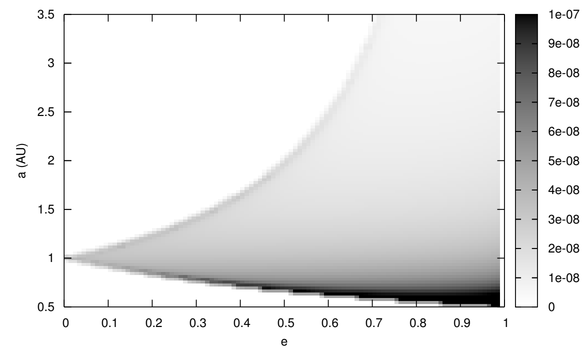

Figure 2: The Earth collision probability per year of Farinelli and Davis (1992) in $a - e$ space (with $i = 1°$). Note especially the ridge along the upper left of the Earth-crossing region corresponding to the heavy selection of pericenter near $q = a(1 - e) = 1$ AU. This is because particles in such orbits are nearly tangent to the Earth's orbit and thus spend a larger fraction of their orbital period near the 1 AU than other orbits. The near-Earth space occupied by the high collision probability orbits along of the bottom of the figure is not heavily populated by NEAs (cf. Fig. 1, upper left panel) and thus contributes few fireballs, despite its high collision probability. For higher inclinations, the collision probability drops monotonically.

For our theoretical model, we have used a sample of modelling published by Bottke *et al.* (2002), kindly provided to us by those authors. This sample consists of 25000 orbits distributed throughout near-Earth space which are consistent with the de-biased NEA orbital distribution; its projection in $a-e$ space is shown in Fig. 1. Although this model represents the distribution in space, the subset of these orbits which actually impact the Earth and thus contribute to the fireball flux will be heavily weighted towards certain types of orbits, specifically, orbits with pericenter near 1 AU and orbits with low inclination (Morbidelli and Gladman, 1998). To model this bias, we calculate the probability per year that an orbit from this distribution would produce an Earth-impacting meteoroid using the algorithm of Farinelli and Davis (1992), based on the formulation of Wetherill (1967). (An implementation was provided by the first authors.) This code calculates the collision probability per unit time for an (a, e, i) triplet assuming that an orbit with this triplet completes a full precessional cycle in longitude of ascending node and argument of pericenter. For reference, Fig. 2 provides a greyscale plot of this collision probability distribution in $a-e$ space. The collision probability per unit time is large for orbits with $a < 1$, but more important for this problem is the enhancement along the "top" of the distribution with $q = a(1-e) \approx 1$ AU, where the NEA population is large (see first panel of Fig. 1).

From these data, we produced a random distribution of fireballs by:

(1) Picking a random (a, e, i) triplet from the NEA distribution

(2) Using the collision probability of that triplet to select whether or not it would impact the earth. If not, we returned to (1).

(3) Generating a random longitude of node for the orbit

(4) Fixing the argument of pericenter such that either the ascending or descending node is within the torus swept out by the Earth, obviously required for a meteoroid orbit to impact the Earth. As the current eccentricity of the Earth is 0.017, this torus has an inner radius of 0.983 AU and outer radius of 1.017 AU.

This allows us to construct databases of arbitrary numbers of orbits described by their five orbital elements. Fig. 1 shows a sample generation of 10000 orbits from the NEA database.

For our second distribution of orbital elements, based on observed fireball data, we obtained a compilation of 652 fireballs in the world-wide literature (provided via Peter Brown, personal communication 2003), the largest such database known to us. This database consists chiefly of fireballs published by the MORP, European, and Prairie networks. Because this fireball database contains a significant cometary component, we filter out all orbits with $e > 1$. In addition, this database classifies each fireball into Type I, II, and III fireballs based on a light-curve data classification system developed by Ceplecha (1977). Type III fireballs are in general cometary, and thus we remove them from the database as well. This leaves a total of 481 presumed meteorite-dropping fireballs. Fig. 1 shows the distribution of these 481 fireballs in $a-e$ space, with the three stream candidates identified. To construct our second fireball model, we discard the longitude of ascending node and argument of pericenter information since we will randomize these two quantities. The (a, e, i) distribution of this compilation may be used to create a second database of arbitrary size via the same procedure outlined for the NEA modelling, except that we do not weight the orbits with collision probability, since has already been accomplished by virtue of the fact that the objects struck the Earth.

We thus possess two suitable models for a random fireball distribution. That is, because of the way in which they are constructed, these Earth-crossing distributions contain no structure in the sense that the angular orbital elements are randomized. This allows us to extract samples of fireballs which will allow us to measure the 'false positive' rate of orbital coincidences, in which light we can examine claims made in support of meteoroid 'streams'.

2.2 Pair Similarity

Table 2 shows two pairs of fireballs with very similar pre-atmospheric orbits. Príbram and Neuschwanstein, in particular, appear to be nearly identical. Spurný *et al.* (2003) quantify this similarity by comparing the orbital elements of these two fireballs via the D' criterion, a variant of the D criterion originially proposed by Southworth and Hawkins (1963) developed by Drummond (1981). For reference, we its definition here:

$$(D')^2 = \left(\frac{e_1 - e_2}{e_1 + e_2}\right)^2 + \left(\frac{q_1 - q_2}{q_1 + q_2}\right)^2 + \left(\frac{\psi}{\pi}\right)^2 + \left(\frac{(e_1 + e_2)}{2}\frac{\theta}{\pi}\right)^2$$

where ψ and θ are given by

$$\begin{aligned}\psi &= \cos^{-1}(\cos i_1 \cos i_2 \ + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2)) \\ \theta &= \cos^{-1}(\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos(\xi_1 - \xi_2))\end{aligned}$$

where ϕ is the ecliptic latitude

$$\phi = \sin^{-1}(\sin i \sin \omega)$$

and ξ is the longitude of perihelion

$$\begin{aligned}\xi &= \Omega + \tan^{-1}(\cos i \tan \omega) & 0 < \omega < \tfrac{\pi}{2} \ \mathit{or} \ \tfrac{3\pi}{2} < \omega < 2\pi \\ \xi &= \Omega + \tan^{-1}(\cos i \tan \omega) + \pi & \tfrac{\pi}{2} < \omega < \tfrac{3\pi}{2}\end{aligned}$$

This criterion is essentially an empirical metric which measures a 'distance' between two heliocentric orbits. Other metrics (exmaple: Valsecchi *et al.* 1999) exist in the literature. In particular, note that D' uses differences in q rather than a, even though the

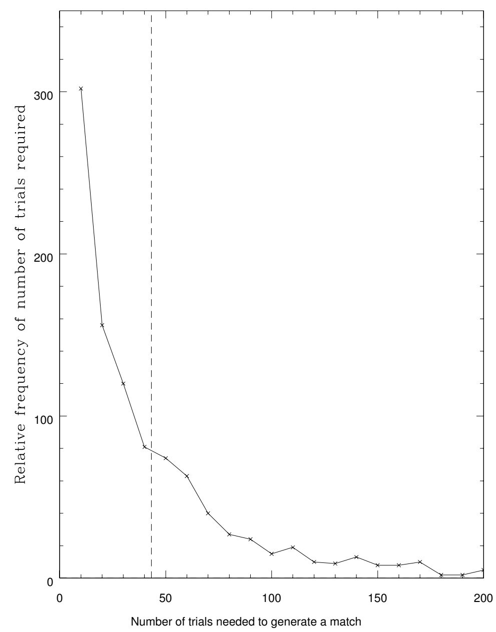

Figure 3: A histogram of the number of trials required to obtain a pair of orbits with $D' < 0.009$. The average number of trials required is 42.4 (shown with a vertical dashed line), while the most likely number of trials falls in the smallest bin of 10 trials.

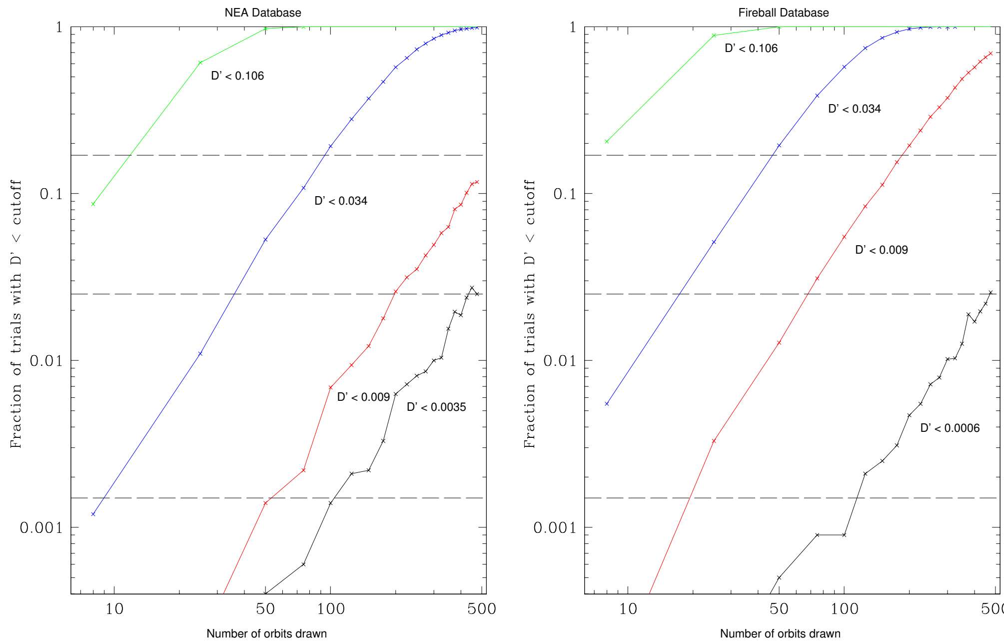

Figure 4: The probability of getting a match in a group of N orbits as defined by some value of D'. The horizontal lines represent one-sided 1σ, 2σ, and 3σ confidence levels (from top to bottom). The orbits were drawn from the fireball database in the right plot, and from the biased NEA modelling on the left. The axes are logarithmic because the increase as a function of N is very steep. The cutoffs we have shown are: Halliday's threshold of 0.106 which he uses to define 'small D''; an Innisfree/Ridgedale level match ($D' < 0.034$); a Príbram/Neuschwanstein level match ($D' < 0.009$); and the D' cutoff required in each case to achieve a 2σ confidence level at 475 orbits (the final curve in each plot).

latter is much more stable against gravitational perturbation. According to this criterion, Príbram and Neuschwanstein are a 'distance' of $D' \approx 0.009$ apart. Spurný *et al.* assessed the probability of obtaining two such fireballs in a data set of size 200 to be of order 1 in 100,000. Although there are more fireballs in the worldwide database against which a match could have been claimed, we begin with this well-defined sample size.

To calculate the expected probability of small D' pairs in a sample of this size, we extract sets of 200 orbits from our NEA-based fireball model using the procedure outlined in Section 2.1 and calculate the value of the D' criterion for each pair of orbits (producing 19900 values). We generate these sets of orbits until a set contains at least one value of $D' < 0.009$. We repeat this process 1000 times, recording the number of sets of orbits generated before a match was found. Fig. 3 shows the results of this process in the form of a histogram. This procedure is simply a series of Bernoulli trials in which each trial has an equal probability of success (where success is defined as producing $D' < 0.009$). Thus, the probability that any given trial will contain such a match is given by the inverse of the average number of trials required for success. This average was calculated to be 42.4, and thus the probability for any given trial is approximately 2.4%. This is a stark contrast to the Spurný *et al.* estimate of 0.001%.

We also wish to investigate how the probability of obtaining a match as close as Príbram/Neuschwanstein increases with the size of the orbital database. To address this, we generated samples of N orbits using the NEA model and noted the value of the best (lowest) D' from all possible pairs, repeating this process 10000 times for each value of N. We stop at $N = 475$ because this is approximately the size of the worldwide fireball database. We repeated the same experiment using our fireball database as the orbital distribution. Fig. 4 shows, for each value of N, the fraction of trials containing at least one value of D' less than a cutoff for several values of the cutoff. We note that, for our NEA-based distribution, the probability of getting as match a close as Príbram/Neuschwanstein reaches of order 10% at 475 orbits. If we only demand even a 2σ departure from 'randomness', the Príbram/Neuschwanstein match fails to provide proof that we can reject the hypothesis that the observed distribution is non-random. Indeed, as indicated in Fig. 4, a D' threshold of 0.0034 is required to claim even a 2σ departure from randomness in our NEA model database.

If we examine the result using the 481-fireball database as our model, the probabilities of obtaining matches are far greater. Indeed, the probability of a match reaches of order 70% for $D' < 0.009$, indicating that virtually all databases of size 475 would contain a match as close as Príbram/Neuschwanstein. An alert reader may argue that the fireball database, as determined by observation, may in fact already contain streams, thus accounting for the large difference the two figures. However, our randomization procedure would have largely destroyed the clusters: Because we randomized the nodal longitude and randomly chosen the argument of pericenter from the values allowing an Earth-intersecting orbit, any two orbits that were nearby in the original database would look very different in our generated samples. To quantify this, we took a single (a, e, i)

triplet and generated 200 orbits with random angles; upon comparing all of these 200 orbits with each other (10900 comparisons), we found that the average value of D' was ~ 0.2. So despite having identical (a, e, i) values, these objects would not be deemed to be members of clusters by the D' technique.

There are several factors which likely account for the increased similarity in the fireball database when compared to the NEA-based model. Although we have accounted for the geometrical collision-probability biasing, the pre-atmospheric orbits of fireballs which really drop meteorties will restricted due to entry speed biases. Orbits with large e and i relative to Earth, and to a lesser extent with large a, will strike the top of the atmosphere at higher speed (see Morbidelli and Gladman 1998 for a figure). As discussed by Wetherill and Revelle (1981), these high-speed entries will suffer greater atmospheric ablation and are less likely to yield fireballs with terminal masses greater than 100 grams. This results in the available orbital parameter space being greatly restricted; the reality of the effect can be easily seen by comparing the upper right and lower left panels of Fig. 1 in which one sees that the high-e region of a, e space is under-represented in the fireball database relative to the collision-biased NEA distribution. We thus feel that our modelling based on the NEA distribution serves as a lower limit to our clustering calculations and the results produced using the 481-element fireball are a better approximation to the truth. We claim that even our analysis using the fireball database is an significant underestimate of the pairing rate, for there is an extremely obvious lack of fireballs in the summer months in our worldwide database (roughly a factor of 4 times as many fireballs during the winter months); this is almost certainly due to the tiny number of dark hours in summer months available for fireball detection in the northern hemisphere where the fireball networks are located and will increase the chance pairing above our randomly distributed nodal longitudes (since $\Omega \sim 90°$ will be avoided). Thus, because a match of $D' < 0.009$ is not remarkable in a world where over 400 fireballs have been compiled, we conclude from our modelling that a Príbram/Neuschwanstein match is not a statistically significant departure from randomness.

2.3 Orbital Clusters

Halliday *et al.* (1990) searched fireball databases and identified 'clusters' of orbits in which each member falls within some D' cutoff of the other members. Drummond (1991) performed a search for streams of asteroids and reported that some of his asteroid streams matched the fireball streams identified by Halliday *et al.* . In this section we examine the claims made by Halliday *et al.* (1990).

Using observations from the MORP camera network operated in western Canada, Halliday *et al.* identified 56 events which they believed to be meteorite-dropping. Combined with 33 events from the Prairie Network, they had a database of 89 meteorite-dropping orbits to be probed for clustering. Unfortunately, the selection process of this sample is non-uniform and somewhat unclear. In comparing each of the 56 MORP objects with the remaining 88 orbits, they found 73 values of D' below their cutoff of 0.106. Based on a calculation from a generated set of 207 'randomized' orbits, they expected that only around 1.5% of the comparisons would be less than 0.106 by chance alone, or in the case of their 89 orbits, only 51 pairs should fall below $D' = 0.106$. They thus concluded that the 89 orbits are more clustered than a randomized sample, indicating that the sample may exhibit clustering. They proceeded to search this fireball sample for clusters of orbits in which each member of the group falls within $D' < 0.087$ of the other members. This search identified 1 cluster of 3 orbits, 2 clusters of 4, and 1 cluster of 5.

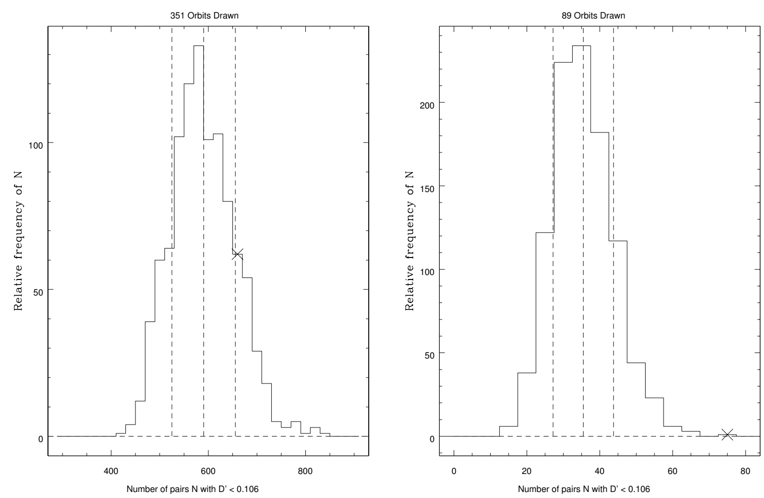

Figure 5: (**Left**): A histogram of the number of orbital pairs with $D' < 0.106$ in 351 orbits with randomized angles selected from the 351 restricted fireball orbits. The location of the real 351 orbit database is marked with an X. The vertical lines are $\pm 1\sigma$ confidence levels. (**Right**): A histogram of the number of orbital pairs with $D' < 0.106$ in 89 orbits selected from the 351 restricted fireball orbits without randomizing angles. Halliday's result of 73 pairs is marked with an X. Clearly, a sample as clustered is Halliday's is very abnormal according to our fireball database.

We attempted to reproduce the first calculation by creating a database of orbits similar in distribution to that in Halliday *et al.* . We pruned our database of 481 fireballs by taking away all fireballs with terminal masses below 100 grams and entry velocities greater than 25 km/s (similar restrictions were used by Halliday *et al.*). This left a database of 351 orbits, whose distribution was shown in Fig. 1. We wished to see if this distribution was consistent with a distribution randomly distributed in Ω and ω. We generated 351 orbits with randomized angles from this database, that is, we created a database with a similar (a, e, i) distribution and of the same size, but with randomized angles. We counted the number of pairs of orbits with $D' < 0.106$, repeating this process 1000 times. The result is shown in Fig. 5. We find that the real fireball database, marked with an X on the plot, does not fall outside a 1σ deviation from a randomized sample; thus, the distribution in the longitude of ascending node and argument of pericenter of the fireball database does not show a significant departure from randomness.

We then attempted to reproduce Halliday's calculation based on their 89 selected orbits. We drew sets of 89 orbits from our 351-fireball database to produce samples equivalent to Halliday's. In this case we did not randomize the node and argument of pericenter, nor did we allow the same orbit to be drawn twice. We compared the first 56 orbits to each of the 89 orbits and recorded the number of orbit pairs with $D' < 0.106$. Fig. 5 shows a histogram for 1000 such trials. We found that in those 1000 samples of 89 orbits only 1 group contained more than 73 pairs. To our surprise we thus find that that Halliday's sample of 89 orbits is significantly more clustered than an *average* sample of fireball orbits from the worldwide database, leading to a puzzle. We have *not* randomized the nodal and perihelion angles of these 89-orbit samples; why, then, should these 89 selected fireballs not be a representative sample of the global fireball database? Halliday *et al.* state that these are a terminal-mass selected sample of MORP and Prairie network fireballs (even though we note that McCrosky *et al.* (1976) claim that the Prairie network fireballs should *not* be used for statistical orbital studies as they are a biased selection). We are unable to determine why the 89-orbit set of Halliday *et al.* is significantly different from the rest of the worldwide collection, and only conclude that this sub-sample appears *not* to be representative of the real pre-atmospheric orbit distribution.

Regardless of the selection bias, the 89-orbit sample did contain clusters of similar fireballs, as noted above. However, we found that this level of clustering may be reproduced from a random distribution. We performed this calculation by drawing 89 (this time randomized in Ω and ω) orbits both from our NEA model database and from our restricted database of 351 orbits using the procedure described in Section 2.1. We searched each sample for one or more clusters with $D' < 0.087$ and noted of the size of each cluster found. For our purposes, we defined a 'cluster' as a set of orbits in which all members were within some D' cutoff of at least one of the orbits. Fig. 6 shows the fraction of 1000 such trials containing a cluster of size at least N orbits as a function of N. We see that a cluster of five orbits (the largest in Halliday's 89-orbit sample) is not a 2σ departure from randomness even in the case of the NEA modelling. In the case of the restricted fireball database, it does not fall outside the 1σ confidence level. We thus reach the same conclusion for orbital clusters as with pair similarity: the clustering identified in the literature is not a sufficiently significant departure from randomness to claim that the global distribution of fireballs is nonrandom.

3 Decoherence of meteoroid streams

Having addressed the question of the false positive rate when searching for evidence of orbital clustering in a distribution which is actually random, we now explore the indepen-

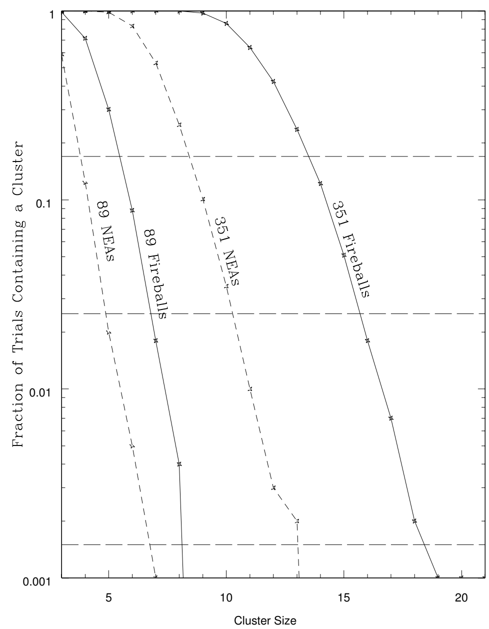

Figure 6: The fraction of groups of 89 or 351 random orbits containing at least one cluster with at least N members as a function of N, where a cluster is defined as N members within D'=0.087 of one of the cluster members. The horizontal lines represent one-sided 1σ, 2σ, and 3σ confidence levels (from top to bottom, respectively). The dashed curves shows the results of drawing orbits from collision-probability biased NEA model; the solid line shows the results when drawing orbits from the fireball database (but with angles randomized). We see in both cases that the fireball distribution is significantly more clustered than a collision-probability-weighted NEA distribution; this is likely due to the additional filtering imposed when selecting meteorite-dropping fireballs from near-Earth orbits. Using the fireball database as a lower limit on expected random clustering, we see that 2σ evidence for non-random clustering would require clusters of 7 fireballs in an 89-elements sample or 16 fireballs in the case of the 351 fireballs, in both cases below what is observed.

dent question of how long such Earth-crossing streams would persist should they exist.

The most obvious mechanism for the creation of a meteoroid stream is the breakup of some parent body, presumably through the collision of a body either entirely in the main asteroid belt or (more likely) on an Earth-crossing orbit. To use the Morbidelli and Gladman (1998) nomenclature, we postulate that the 'immediate precursor body' (that in which the objects existed just before a collision created the fragment that later hits the top of the Earth's atmosphere) was an object already in Earth-crossing space. The arrival of a coherent, confined stream from a non-Earth-crossing to an Earth-crossing orbit is much more difficult than itsshort-term survival due to the extremely chaotic nature of the delivery process to Earth-crossing orbits (Gladman *et al.* 1997); we shall return to this point below. We turn first to the question: if the three fireballs listed in Table 1 are each members of orbital streams of material, how long could these structures survive in a coherent sense? That is, how long would the meteorites being delivered to Earth appear to come from similar pre-atmospheric orbits or, even less restrictively, fall on similar days even if their orbits are unknown?

We have addressed this question by conducting extremely detailed numerical simulations of the three candidate streams for time scales of a few hundred thousand years. We take the initial state of the stream to be a suite of test particles orbiting on initially identical Keplerian ellipses differing only in a random mean anomaly along the orbit. It is easy to show (see, *eg.*, Harris 1993) that even for tiny initial 'break up speeds' of < 10 meters per second for fragments escaping a hypothetical initial breakup, Kepler shear along the orbit will spread the fragments out around the entire orbit in only a few thousands of years; we performed a trivial numerical simulation to confirm this.

We created initial streams in the orbits of Table 1, taking the 5 measured orbital elements and adding a mean anomaly randomly selected between $0°$ and $360°$ (using mean anomoly rather than true in order to populate the orbit evenly according to the time spent along the orbit). We generated 20 022 such particles for each stream. All 9 planets were included in the simulations. Simulations proceeded for 150,000 or 500,000 years of simulated time, with a 'base' time step of 0.003 years (≈ 1 day), which is automatically sub-divided by the integrator upon close approach to a planet. Test particles are removed from the integration if they collide with a planet or the Sun, or if they receeded to a distance of 1000 AU from the Sun (at which point they were clearly not part of an orbital stream). The integrations were conducted on the Leverrier 94-CPU Beowulf cluster at the University of British Columbia, requiring about five CPU-years of computational effort per simulation.

The simulations were conducted with the symplectic integrator `swift_skeel`. This numerical algorithm is a minor variant of the SYMBA integrator (Duncan *et al.* (1998)) which efficiently integrates the equations of motions of a Solar System problem (i.e., dominated by a central mass). This algorithm is a full and explicit numerical integration in 3-dimensional space without making the kinds of approximations done in Monte-Carlo models; in particular, the nodal longitudes of the orbits of all particles are accurately tracked. We produced a modified version of skeel that logs information about all planetary close passages (that is, when the integrator detected perigee passage within 0.01 AU of Earth). This logging is necessary because, even with this huge number of test particles, direct impacts onto Earth are rare given Earth's small cross-section and the short time scales over which the turn out to streams survive. The close passages tell us when portions of the stream may strike Earth, and will clearly demonstrate how quickly the stream loses a spatially-coherent character.

We interpret our numerical investigations for the purposes of this paper in two ways. In the context of discussion of Dodd *et al.* (1993) and Lipschutz *et al.* (1997), we wish to examine over what duration an initially tightly-confined stream would produce meteorite falls which are confined in time. Using the Lipschutz *et al.* (1997) identification of Peekskill as a member of a stream with total 'day-of-fall spread' of about two weeks, we adopt a similar criterion. Such a two-week concentration implies that the nodal longitudes of the meteorite falls in question were within a $\approx 14^\circ$ band.

We first describe the integrations qualitatively. We begin with a stream of material which, because the objects on which our three simulations are based struck the Earth, have either an ascending or descending node very close to 1 AU from the Sun. As time advances this quickly ceases to be true as the secular precession induced on the particle orbits cause them to precess by both regressing their longitude of node (twisting the orbital plane) and advancing their argument of perihelion (which changes the distance of the nodes from the Sun). Thus, in short order the intersecting state of the Earth's and stream's mean orbit ceases as the node of the stream in question moves either outside or inside of roughly 1 AU. This orbit-intersecting state will re-occur once the argument of pericenter advances far enough to bring the stream's orbital ellipse back into contact with Earth's orbit; this usually occurs four times per precession cycle although more complex geometries are possible.

We plot two different aspects the nodal evolution of our Peekskill stream over the first 100 kyr in Fig. 7. First, we plot the orbital elements of all surviving particles at 1000-year intervals; in Fig. 7 the vertical strips at these time intervals show the longitude of ascending and descending node of *all* particles; in particular these particles could have any other orbital elements (*eg., a/e/i*) and need not have an ascending or descending node near 1 AU from the Sun to allow for a possible collision with Earth. We see Ω regressing as expected, with the 'center' of the cluster of particles taking about 40,000 years to regress 360 degrees. Although this representation allows us to see that in about ~ 40 kyr (only one precessional cycle) the stream's nodes have sheared out to cover all possible values, this does not necessarily indicate that all coherent character is gone as there *could* be correlations between the orbital elements such that those particles with nodal distances of ~ 1 AU are restricted to certain ranges of Ω. We experimented with simply singling out orbits with nodal distances of 0.983–1.017 (that is, between Earth's perihelion and aphelion distances), hypothesizing that each integrated particle could be imagined as representing an osculating orbit with particles spread out uniformly around

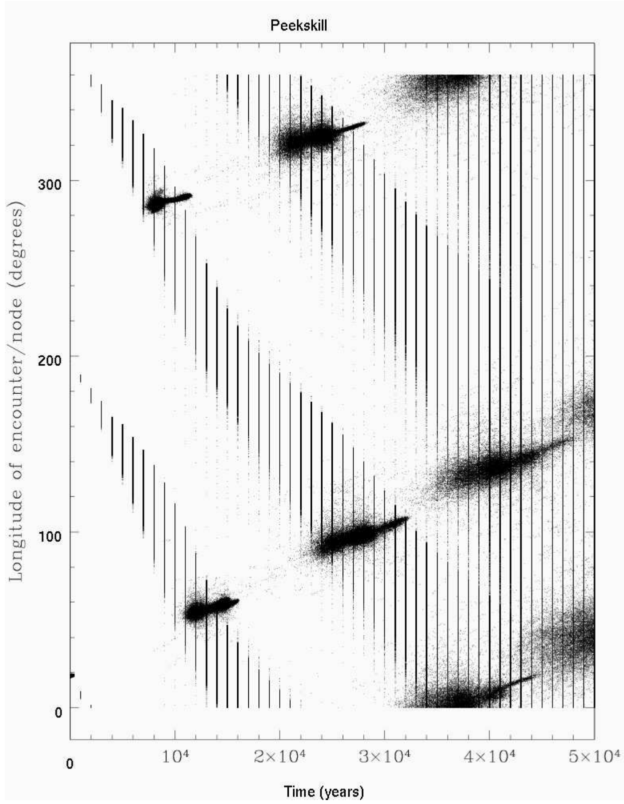

Figure 7: Two representations of the early (50,000) dynamical evolution of our "Peekskill stream". The vertical bars (at our 1000-year dump interval) indicate the longitudes of ascending *and descending node* of all surviving particles, regardless of the heliocentric distance of that node. The individual points (which are progressively less heavily clustered) show the ecliptic longitude (roughly day of fall) for integrated particles which actually pass within 0.01 AU of the Earth and thus could strike the Earth; the streaming effect is much more clearly seen here than in Fig. 8 as the nodes of the stream's orbit occasionally pass through 1 AU from the Sun. The vertical axis corresponds to the longitude of ascending node for the 1000-year period sampling, or to the ecliptic longitude (relative to the J2000 ecliptic) for close encounters. Note that there is a very tightly-confined clump of close encounters near 20° at the start of the integration corresponding to the initial node-crossing state.

that orbit in mean anomaly and thus any nodal intersection of that orbit could result in a collision producing a meteorite. However, perhaps having an intersecting orbit was not enough: in principle correlations might exist which result in particles with intersecting nodes to be confined away from the Earth. To alleviate these doubts, we have resorted to extremely intensive logging of all close fly-bys of Earth (typical outputs are 30 Gbytes per simulation) in order to identify the ecliptic longitudes of close encounters. The dots of Fig. 7 show the ecliptic longitude of the close encounters, where now we feel secure in saying that these flybys could produce fireballs by a very tiny timing difference between the integrated particle and one extremely close in parameter space. Thus, this representation shows the distribution of day of fall from our initially tightly-confined orbital stream. It is easy to see each node-crossing of the stream, and the gradual de-coherence of the orbital stream's close encounters. Tight clumping of close encounters persists for the first 50 kyr. Fig. 8 presents the close-encounter longitudes for all three numerical integrations. The simulations ran for 500 kyr, except for the 150 kyr Príbram integration which was stopped sooner as it was clear that the stream was already essentially decoherent by 100 kyr. In each case we see an initially tightly-confined state spread rapidly out so that falls would become widely dispersed throughout the calendar year. Fig. 8 shows that by 100-200 kiloyears, the encounters of these streams, and hence the days of fall of its members, are nearly uniformly distributed over the whole possible year. This conclusion is qualitative (although clearly very strong) in that we have not implemented some sort of 'cluster finding' algorithm which quantitatively (with an arbitrary measure of 'concentrated') finds concentrations in the encounter longitudes. At the end of the integrations there is still some mild residual non-randomness, but only at the level that falls in a given half of the year are slightly more probable than in the other half; these concentrations do not of course allow for tightly-correlated clusters like those being examined. Therefore, we conclude that on time scales of $\ll 1$ million years these Earth-crossing streams become completely decoherent in terms of a detectable concentration relative to the general background of Earth-crossing material.

A few comments on each of the three integrations are appropriate.

Due to the high inclination, relatively deep perihelion distance q, and large semimajor axis a of Príbram, this stream has relatively 'fast' node crossing events due to its high precession rateand has fewer encounters per unit time than the other streams we integrated. The fact that the aphelion is near Jupiter means that this stream suffers very strong differential shear in the precession rates. Of the three streams we examined, this is the *worst* candidate for an orbit which could keep a coherent character, requiring only of order 50,000 years to decohere.

The Peekskill stream requires $\sim 0.2 - 0.3$ Myr before losing coherence. Its low (5 degree) inclination results in many more encounters per unit time; this is clearly not as effective (considering the Príbram integration) as the near-presence of Jupiter for disrupting the stream-like character, but nonetheless is far below the cosmic-ray exposure age of Peekskill itself.

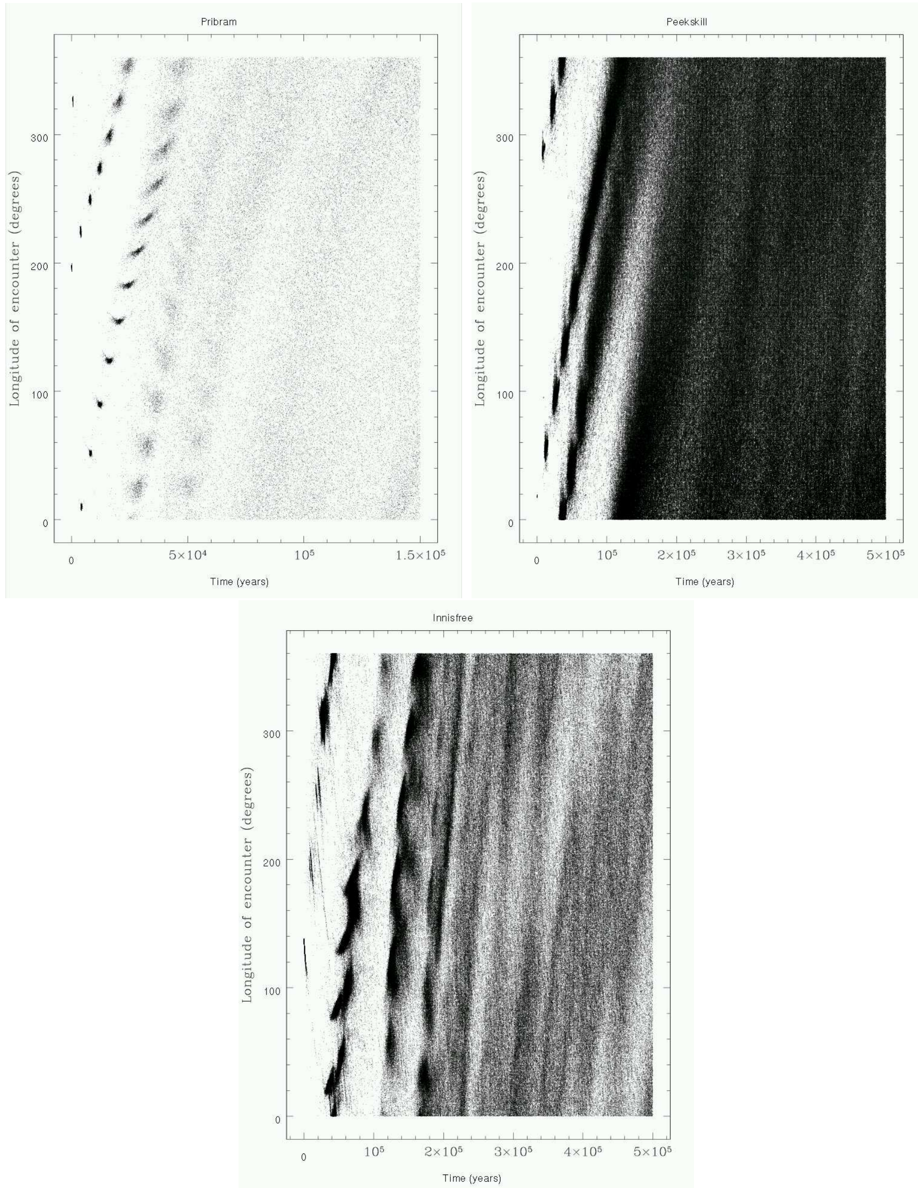

Figure 8: The longitude of encounter for all particles experiencing close encounters with the Earth. Although the eye is drawn to what appears to be a forward precession of the encounter longitudes, there is in fact a rapid *regression*. However, in one nodal precession period, the encounter longitude advances slowly; this is more easily seen in Fig. 7

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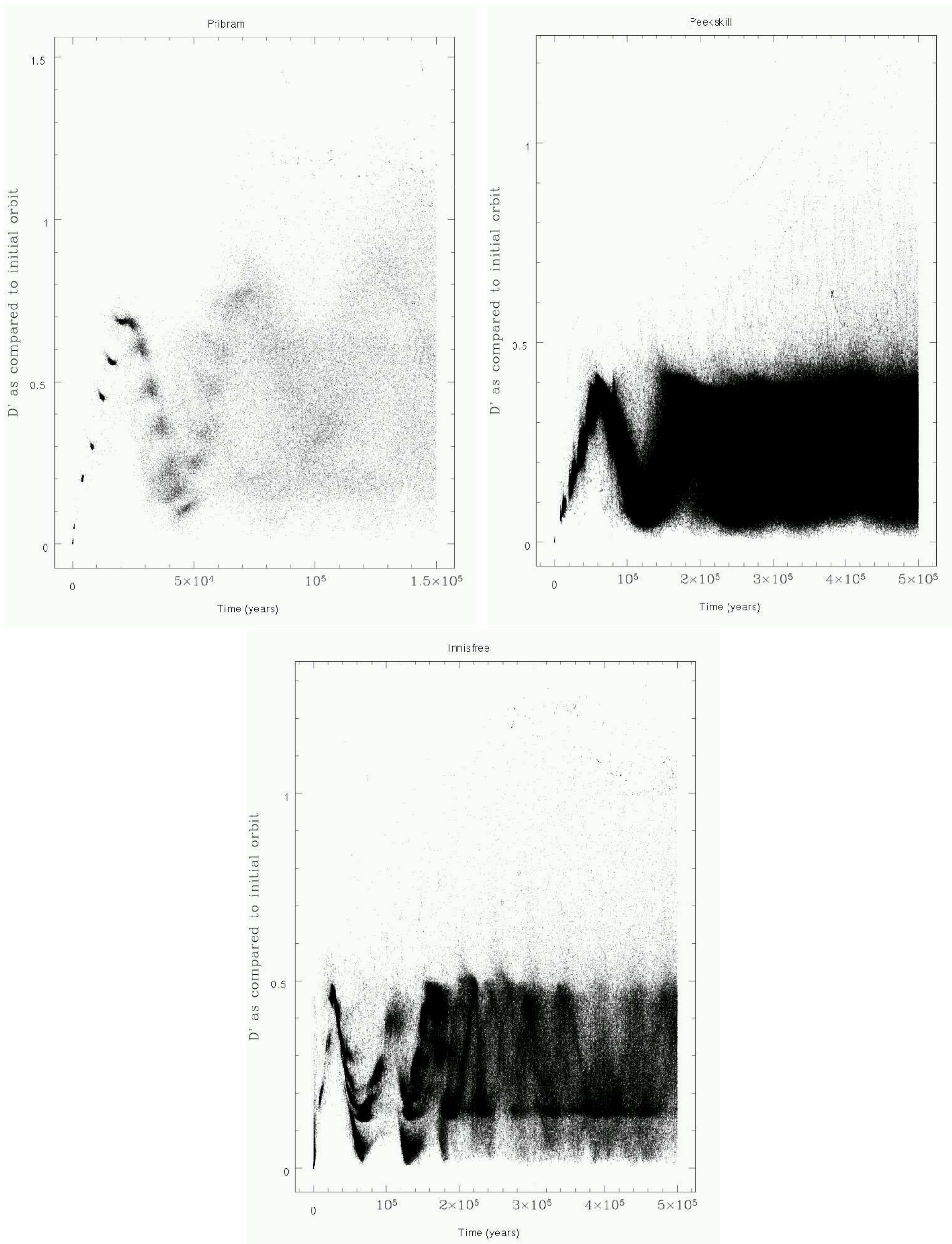

Figure 9: The value of the D' criterion as compared to the initial orbit for Príbram, Peekskill, and Innisfree. The values are initally tightly confined, but begin to lose coherence. One can barely distinguish any sort of “stream” at about 150000 years for each.

Innisfree's integration is interesting near the very beginning of the simulations due to the sharp features corresponding to a set of close passages tightly clumped in encounter longitude, where the longitude rapidly regresses with time. This effect is caused by a combination of factors. First, Innisfree has a high (12°) inclination and perihelion distance q=0.983 which is just barely inside the Earth. Thus, the encounter speeds are relatively high and confined to a well-defined longitude when a node is Earth intersecting at 1 AU. This node regresses rapidly until it decouples. But the tight confinement means that the encounter geometries of the particles whose paths are deflected by the Earth are similar, and thus these objects are deflected to a new concentration in (a, e, i) space with a different precession period; this clump arrives back to node crossing at a slightly different time than the main stream. Careful inspection of the integration shows the subsequent detaching of more and more 'sub-streams'; this collective behaviour only lasts a few hundred thousand years before the differential shear again randomizes the nodes of the Earth-encountering particles, again far less than Innisfree's 27 Myr CRE age.

Because orbital similarity is determined using the D' criterion, we also plot the evolution of that criterion over time (Fig. 9). However, because the D' criterion compares two orbits, examining the future evolution of the stream is not clear, because some method must be available to determine the 'center' of the stream. Because of the rapid decoherence observed we have chosen to simply pick the initial orbit for this comparison. Thus, although the stream's orientation precesses and so will not remain near $D' = 0$ as compared to the initial orbit, it should remain tightly confined around some non-zero value if a stream is present. In Fig. 9 one sees that this is initally the case but as these streams evolve due to secular precession the D' values begin to spread out. The stream-like appearance is lost on the order of hundreds of thousand years.

From these examples we conclude that the maintenance of stream-like behaviour for the longest possible time in an Earth-crossing stream will be best for orbits which (1) have high inclination, (2) are deeply Earth-crossing, and (3) have small semi-major axis so that aphelia are far from Jupiter. Although we have not explored this, it is likely that only a factor of a few in decoherence time could be gained for realistic fireball-producing orbits. It is clear, however, that the kind of tight clumping envisioned in the literature claims for meteorite streams (encounter longitudes confined to very much less than a month) persists for $\ll 1$ million years for the candidate streams in question.

4 Discussion and Conclusions

We have analysed simulated fireball databases of size comparable to the current world-wide database generated from both a collision-probability-weighted NEA modelling and from randomization of real fireball orbits to determine the statistical signifance of evidence for meteoroid streams. We find that a pair of orbits as similar as Príbram and Neuschwanstein (measured using the D' criterion) occur $\simeq$70% of the time by random chance in a fireball database consisting of a world-wide sample of 481 orbits distributed in a (a, e, i) distribution similar to the observed fireballs but whose other angles are randomized. Even using our (probably insufficiently restrictive) fireball model based upon a model NEA distribtuion gives a chance occurence of a $D' = 0.009$ pair at the 10% level. Thus, our work shows one cannot reject the null hypothesis at even the 2σ level; that is, the existence of this pair is consistent with random chance.

Additionally, we have shown that the multiple-member streams of Halliday *et al.* (1990) found via D' clustering also do not constitute 2σ departures from randomness; random sets of fireballs show similar frequency of such clumps. We conclude that the current level of departure from randomness in the worldwide fireball database is statistically insignificant.

We should be clear that we are not saying that the D' metric is suspect or non-useful. This metric's usefulness in the detection of cluster must simply be rigorously calibrated by determining the false-positive rate in a given sample; Jopek *et al.* (1999) present such a reliability determination for a clustering method applied to meteor orbits. Our conclusion is that the orbital parameter space over which real meteorite-dropping fireballs come from is so restricted that many positive hits occur by chance; so many that nearby D' pairs or clusters become nearly certain once the database becomes large. A clustering claim must simply be shown to occur less frequently than 3 times in 100 to have 2-sigma evidence. As a concrete example (Fig. 6), in an 89-fireball database a cluster of 8 fireballs all with $D' < 0.087$ from some reference orbit *would* constitute a 3-sigma departure from random chance (a cluster of 7 would be a borderline 2σ variation), and a cluster of 16 fireballs are required for a 2σ departure in a 351-orbit database. The worldwide database has no such features indicating a significant departure from uniformity.

Using our numerical orbital evolution calculations we find that in three stream-candidate cases a tightly-confined stream on the fireball's orbit became decoherent in at most a few hundred thousands years. We thus reject the streaming hypothesis for the orbital similarity of Príbram and Neuschwanstein because not only are their CRE ages both much longer than the stream decoherence time, but they are also 36 Myr apart. They cannot have received the majority of their exposure while in a coherent Earth-crossing stream. We thus believe that either (i) they were exposed for millions of years before entering the stream, perhaps because the were located on or near the surface of some non-homogenous parent body (due to their different petrographic type), or (ii) the similarity is pure coincidence. The former suggestion was explored by Morbidell and Gladman (1998), but could not explain the large difference in the exposure ages (12 versus 48 Myr). We thus conclude that the most likely explanation is chance alone.

The reader might object that surely the fact that there is a $D' < 0.009$ pair in the *recovered* fireball set (of a half dozen) must surely be significant. Even though we calculate the probability of a $D' < 0.009$ match with only six fireballs is of order 10^{-4} (and thus seems signficant) we are *very* uncomfortable with this line of a reasoning. It is a 'post facto' examination of the data set where one has found a reason 'after the fact' to cut the data set in this way. Why should there be anything special about the fact that these particular fireballs were recovered (except perhaps a mild mass bias?). To address this we asked the question : *If* the Earth-crossing population contains a group of meteorite-dropping objects which have resulted in roughly one-sixth of the large recovered fireballs coming from a single stream, what is the probability that only 6 other fireballs (identified by Spurny *et al.* 2003, including Neuschwanstein) have $D' < 0.105$? We generated a new database starting with our 351-orbit data set and added enough fireballs with $D' \sim 0.01$ (with respect to Príbram) to make Príbram/Neuschwanstein matches occur about one-sixth of the time (that is, we 'inserted' a tightly-correlated stream into a uniform background). We then picked samples as before, but only randomized the angles of the 'non-Príbram stream particles' to preserve a stream. Unsurprisingly, we found that almost all 351-orbit samples (reflecting what would be in the worldwide catalogue) drawn from this distribution had ~ 50 Príbram-like fireballs, whereas the worldwide collection has 7. We calculated that the probability of getting less than 29 Príbram-like fireballs is 1 in a million; the probability of getting only 7 is thus $\ll 10^{-6}$. We therefore conclude that the postulate of a meteoroid stream near the orbit of Príbram is inconsistent with the available information.

The most likely production method for a real meteoroid stream would be the catastrophic fragmentation of an asteroid *already* on an Earth-crossing (because the time scale to reach an Earth-crossing orbit is likely longer than the coherence time of a stream produced with $q > 1.1$ AU). Once produced, the Earth-crossing stream could persist for $\sim 10^5$ years before disruption. Actually detecting this Earth-crossing stream in the fireball databse would require that the stream produce a sufficient number of falls to generate a statistically-significant signal over the background; this is not simple as the Earth-crossing meteoroid population is huge and the disrupted fragment would have to supply $\sim$1% of the Earth-intersecting population to give several orbit-determined fireballs in the 351-orbit database. The meteorite-producing flux at the top of Earth's atmosphere is estimated by Halliday *et al.* (1989) to be $\sim$30,000/year over the entire planet, a rate which Bland *et al.* (1996) concludes has remained roughly constant over the last 50,000 years. Thus roughly 300 fireballs/year from a stream would be required, with a collision of optimistically perhaps 10^{-7}/year (for a perihelion tangent to the Earth's orbit) this requires a stream population of $\sim$3 billion meteoroids. An excessively optimistic estimate would be that an original asteroid was shattered into exactly 3 billion 10-cm fragments (big enough to give recoverable meteorites, but small enough to keep the asteroid size managable) for an asteroid diameter of $\sim$200 m (with a 100% packing fraction). A more realistic mass distribution for the fragments from this collision or disruption would require an 'immediate precursor body' larger by a factor of at least several; below we work with a ~ 1 km diameter estimate. The time interval between *collisional* catastrophic disruption of km-scale NEAs is >1 Myr (Bottke 2004, personal communication). Catastrophic *tidal* disruption due to a close terrestrial passage (Richardson *et al.* 1998) might be a more effective way to disrupt a parent asteroid. Thus, while it is not impossible to imagine a

D ~1 km asteroid with $q \simeq 1$ AU being dispersed within the last 10^5 years by collisional or tidal action in order to provide a stream, but such a hypothesis would yield the following situation:

1. The probability of this occuring in the last 50 kyr is low. The rate of catastrophic tidal disruption is about 1 per 400 000 years (Bottke *et al.* (1998)), where we have halved the rate to account for a recent factor of roughly 2 drop in the estimated 1-km NEA population), and catastrophic collisional disruption of 1-km NEAs is even less frequent.

2. If we define $d \sim 3$ meters to be the depth to which CRE exposure can occur, then only a fraction $\sim 3d/D$ of the immediate precursor body would have been exposed to cosmic ray flux before the disruption. For the unrealistically optimistic $D = 200$ m this is $< 3\%$ of the volume of the asteroid, so >97% of the stream fireballs should have CRE ages <50 kyr, in blatant conflict with reality. Halliday *et al.* (1987) identified this problem for Innisfree, stating that only 8% of the Innisfree stream would be fragments which should show any reasonable CRE exposure (with the remainder being shielded until the recent breakup which would be needed to create the stream). Interestingly, Peekskill shows evidence for a complex CRE history (Graf *et al.* 1997) with a second stage exposure of <0.2 Myr; this is what would be expected for a near-surface 'chunk' of the immediate precursor body. However, the fact that the other candidate meteorites in the candidate Peekskill 'stream' are not dominantly very low ($\ll 1$ Myr), CRE age chondrites rules out (from our point of view) any possibility that this is the result of a recent catastrophic fragmentation.

Our conclusion is that there is as yet no compelling evidence that there is any significant orbital correlation shown by the orbital distribution of the fireball population.

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References

Bland T., Smith T., Jull A.J.T., Berry F., Bevan A., Cloudt S., and Pillinger C. (1996) The flux of meteorites to the Earth over the last 50 000 years. *Monthly Notices of the Royal Astronomical Society*, **283**, 551-565.

Bottke William F., Richardson D., and Love S.G. (1998) Production of Tunguska-sized bodies by Earth's tidal forces. *Planetary and Space Science*, **46**, 311-322.

Bottke William F., Morbidelli A., Jedicke R., Petit J., Levison Harold F., Michel P., and Metcalfe Travis S. (2002) Debiased Orbital and Absolute Magniutde Distribution of the Near-Earth Objects *Icarus*, **156**, 399-433.

Brown P., Ceplecha Z., Hawkes R., Wetherill G., Beech M. and Mossman K. (1994) The orbit and atmospheric trajectory of the Peekskill meteorite from video records. *Nature*, **367**, 15-39.

Ceplecha Z. (1977). Fireballs Photographed in Central Europe. *Bull. Astron. Inst. Czech.*, **28**, 328-340.

Dodd Robert T., Wolf Stephen F., and Lipschutz Michael E. (1993) An H Chondrite Stream: Identification and Confirmation. *Journal of Geophysical Research*, **98**, 105-118.

Drummond J. D. (1981) A test of comet and meteor shower associations. *Icarus*, **45**. 143-153.

Drummond J. D. (1991) Earth-approaching asteroid streams. *Icarus*, **45**. 143-153.

Duncan M., Levison H., and Man Hoi L. (1998) A Multiple Time Step Symplectic Algorithm for Integrating Close Encounters. *Astronomical Journal*, **116**, 2067-2077.

Farinella P. and Davis D.R. (1992) Collision rates and impact velocitites in the main asteroid belt. *Icarus* **97**, 111–123.

Gladman B., Migliorini F., Morbidelli A., Zappala V., Michel P., Cellino A., Froeschlé Ch., Levison H., Bailey M., and Duncan M. (1997) Dynamical lifetimes of objects injected into asteroid belt resonances. *Science*, **277**, 197-201.

Graf T. and 20 co-authors. (1997) Exposure history of the Peekskill (H6) meteorite. *Meteoritics and Planetary Science*, **32**, 25-30.

Halliday I., Blackwell A, and Griffin A. (1978) The Innisfree meteorite and the Canadian Camera Network. *Journal of the Royal Astronomical Society of Canada*, **72**, 2749-2784.

Halliday I. (1987) Detection of a meteorite "stream": Observations of a second meteorite fall from the orbit of the Innisfree chondrite *Icarus*, **69**, 550-556.

Halliday I., Blackwell A., and Griffin A. (1989) The flux of meteorites on the Earth's surface. *Meteoritics*, **24**, 173-178

Halliday I., Blackwell A., and Griffin A. (1990) Evidence for the existence of gruops of meteorite-producing asteroidal fragments, *Meteoritics*, **25**, 93-99

Halliday I., Griffin A., and Blackwell A. (1996) Detailed Data for 259 Fireballs from the Canadian Camera Network and Inferences Concerning the Influx of Large Meteroids. *Meteoritics*, **31**, 185-217.

Harris A. W. (1993) Corvid meteoroids are not ejecta from the Giordano Bruno impact.

Journal of Geophysical Research, **98**, 9145-9150.

Jopek T., Valsecchi G., and Froeschlé Cl. (1999) Meteroid streams identification: a new Approach -II. Application to 865 photographic meteor orbits. *Monthly Notices of the Royal Astronomical Society*, **304**, 751-758.

Lipschutz M. E., Wolf S., and Dodd R. (1997) Meteoroid streams as sources for meteorite falls: a status report, *Planetary Space Science*, **45**, 517-523.

McCrosky R. E., Shao C.-Y., and Posen A. (1976). Prairie Network Fireball Data. I. Summary and Orbits. *Center for Astrophysicists Preprint Series*, No. 665, Cambridge, MA.

McCrosky R. E., Shao C.-Y., and Posen A. (1979). Prairie Network Fireball Data. II. Trajectories and light curves. *Center for Astrophysicists Preprint Serieis*, No. 721, Cambridge, MA. Also, in Russian, *Meteoritika*, **38**, 106-156.

Messenger S. (2002) Opportunities for the stratospheric collection of dust from short-period comets. *Meteoritics & Planetary Science*, **37**, 1491-1505.

Morbidelli A. and Gladman B. (1998) Orbital and temporal distributions of meteorites originating in the asteroid belt. *Meteoritics & Planetary Science*, **33**, 999-1016.

Richardson D.C., Bottke W., and Love S. (1998) Tidal distortion and disruption of Earth-crossing asteroids. *Icarus*, **134**, 47-76.

Southworth R. B. and Hawkins G. S. (1963) Statistics of meteor streams. *Smithsonian Contributions to Astrophysics*, **7**. 261-285

Spurný P., Oberst J., and Heinlein D. (2003) Photographic observations of Neuschwanstein, a second meteorite from the orbit of the Príbram chondrite. *Nature*, **423**, 151-53.

Valsecchi G., Jopek T., and Froeschlé CL. (1999) Meteroid streams identification: a new Approach -I. Theory *Monthly Notices of the Royal Astronomical Society*, **304**, 743-750.

Wetherill G. W. (1967). Collisions in the Asteroid Belt. *Journal of Geophysical Research*, **72**, 2429-44.

Wetherill G. W., and ReVelle D. O., (1981). Which Fireballs are Meteorites? A study of the Prairie Network Photographic Meteor Data. *Icarus*, **48**, 308-28.