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THE PROBLEM OF LINKING MINOR METEOR SHOWERS TO THEIR PARENT BODIES: INITIAL CONSIDERATIONS

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Abstract. Efforts to link minor meteor showers to their parent bodies have been hampered both by the lack of high-accuracy orbits for weak showers and the incompleteness of our sample of potential parent bodies. The Canadian Meteor Orbital Radar (CMOR) has accumulated over one million meteor orbits. From this large data set, the existence of weak showers and the accuracy of the mean orbits of these showers can be improved. The ever-growing catalogue of near-Earth asteroids (NEAs) provides the complimentary data set for the linking procedure. By combining a detailed examination of the background of sporadic meteors near the orbit in question (which the radar data makes possible) and by computing the statistical significance of any shower association (which the improved NEA sample allows) any proposed shower–parent link can be tested much more thoroughly than in the past. Additional evidence for the links is provided by a single-station meteor radar at the CMOR site which can be used to dispel confusion between very weak showers and statistical fluctuations in the sporadic background. The use of these techniques and data sets in concert will allow us to confidently link some weak streams to their parent bodies on a statistical basis, while at the same time showing that previously identified minor showers have little or no activity and that some previously suggested linkages may simply be chance alignments.

Keywords: Asteroids, comets, meteor showers, meteor radar

1. Introduction

Much work has been done in attempting to link minor meteor showers to their parent bodies. Major meteor showers have been exclusively associated with comets, with the exception of the Geminids and Quadrantids which are generally considered to be linked to bodies currently displaying no cometary activity (3200 Phaethon and 2003 EH1). Are some minor showers connected to weak or faint comets or even to extinct comets? The question of whether asteroids might be associated with minor showers is of particular interest. Efforts to find the parent bodies of minor showers have been impeded primarily by two factors: the incompleteness of our knowledge of the near-Earth asteroid/comet population and the scarcity of accurate meteor orbits for weak showers. The first problem has been alleviated over the last decade as the sample of near-Earth asteroids (NEAs) has grown considerably due to the activity of large surveys such as Spacewatch, the Lincoln Near-Earth Asteroid Survey (LINEAR) and the Lowell Near-Earth Object Search

(LONEOS). As of this writing there are over 2800 known NEAs, defined as having perihelia $q < 1.3$ AU (Minor Planet Center, http://cfa-www.harvard.edu/iau/mpc.html) and 1516 single-apparition and 155 multi-apparition comets (Marsden and Williams, 2003). The second difficulty, that of obtaining accurate orbits for minor showers, has been addressed by the success of meteor patrol radars such as the Advanced Meteor Orbit Radar (Baggaley, 2001) and the Canadian Meteor Orbit Radar (Webster et al., 2004). The latter has collected over one million meteor orbits over the last 2 years and continues to accumulate them at a rate of about 2500 a day. It is this data set that we will use in our analysis. Using these two new data sets and a multiplicity of criteria for making stream–parent associations, the links between meteor showers and their sources can be made with confidence.

2. The Canadian Meteor Orbit Radar (CMOR)

The Canadian Meteor Orbit Radar (CMOR), located at 43.2° N, 80.7° W near Tavistock, Ontario, is described in detail by Webster et al. (2004). The radar measures several thousand meteoroid orbits per day to a limiting radio magnitude of +8 or an equivalent meteoroid radius of approximately 100 microns. The velocity for all echoes detected at three separate sites is measured using the time-of-flight technique (cf. Baggaley 2002). Comparison with major meteor showers that have known out-of-atmosphere velocities allows correction for atmospheric deceleration and yields a final mean velocity error of order 5% in the individual velocity measurements. Errors for each orbit are computed based on the measured errors in the time delays.

3. Criterion 1: Checking the background

A complicating factor in the study of minor showers is the ever-present sporadic background. Is a group of measured meteor orbits a true shower or a simple statistical fluctuation in the background flux of meteors? In order to disentangle the two phenomena, good measurements of the (non-uniform) background are needed. What is needed is to search for enhancements in the meteoroid orbit density in the five-dimensional orbital element space and determine if these are sufficiently elevated above the density seen at nearby orbits. CMOR provides the wide-coverage and long-time baseline data set needed to reliably extract weak showers from the background as the large data set reduces the statistical noise dramatically.

In order to search for enhancements in the meteor flux, we adopt the technique presented by Steel (1995) of computing a restricted D criterion based only on a, e and i for an asteroid against a sample of meteoroid orbits, and plotting the result versus longitude of perihelion ϖ. The restricted D criterion used is (Asher et al., 1994)

$$D^2 = \left(\frac{a_1 - a_2}{3}\right)^2 + (e_1 - e_2)^2 + \left(2\sin\frac{i_1 - i_2}{2}\right)^2. \quad (1)$$

The procedure is as follows. Some arbitrary asteroid orbit is selected. The D parameter above (which does not include the angular elements) is computed between this test asteroid orbit and *all* the meteoroid orbits in the database. All the asteroid–meteor pairs with D below some cutoff value (in this case we arbitrarily choose $D < 0.2$) are kept. A histogram (Steel uses a polar plot but we find a histogram is more useful given the size of the dataset involved) is then constructed of the number of meteoroid orbits that pass our low-D filter, as a function of the meteoroids' ϖ. In effect this procedure asks the question, "At any given ϖ, how many meteoroids have orbits with a, e and i close to that of the asteroid in question?" This provides a measure of the sporadic background as, for most values of ϖ, any meteoroids with low D values are simply sporadics which are only coincidentally associated with our test asteroid orbit. If an enhancement exists at the longitude of perihelion of the asteroid itself, however, this indicates a possible excess of orbits consistent with meteoroids being produced recently (i.e. within one precession cycle) from the asteroid itself. This method is designed to find young showers that have suffered little or no orbital evolution. Older streams, having undergone significant differential orbital precession from their source, will not be detected by this technique.

This work is still ongoing, but we present here some of our initial results. Figure 1 shows the outcome for two NEAs, 1998 SH2 and 2004 HA1. Both show an uneven and varying background, but with small distinct enhancements at the location of the asteroids' longitude of perihelion (shown by the vertical line).

Once enhancements in the orbital distribution have been extracted, the full D parameter (in practice, we use the D' parameter of Drummond (1981) rather than the standard D of Southworth and Hawkins (1963)) between likely source asteroids and the nominal orbits of meteor showers can be computed, and a search made for small values of D indicating possible associations.

This is usually the first step (and the only one that can be performed in the absence of a large meteor orbit database) in most shower association studies, but here it is motivated initially by the results of the radar data. Table I lists a few NEAs with observed radar enhancements and nearby minor showers (Cook, 1973), along with their Tisserand parameter T_J relative to Jupiter and their relative D' (Drummond 1981).

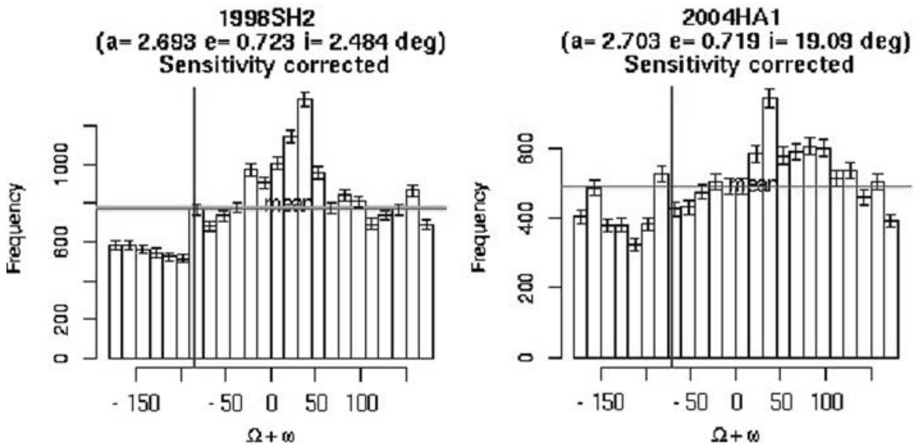

Figure 1. Histograms of the number of meteor orbits from the CMOR data base with $D < 0.2$ with respect to two NEAs, as a function of ϖ. The vertical line indicates the longitude of perihelion of the asteroid, the horizontal line the average number of orbits per bin. The uncertainties shown on the histogram bars are $\sqrt{N}$ to give an indication of the statistical noise. The meteor numbers have been weighted to compensate for the varying collecting area of the radar for radiants at different declinations.

TABLE I
A few NEAs with an observed excess of meteor orbits in their vicinity that lie near known minor showers (taken from Cook (1973))

	a	e	q	i	ϖ	T_j	D'
2004 HA1	2.704	0.719	0.759	19.1	288.1	2.870	
α Bootids	2.586	0.710	0.750	18.0	283.0	2.955	0.028
1998 SH2	2.693	0.723	0.745	2.5	274.3	2.924	
σ Leonids	2.206	0.660	0.750	1.0	276.0	3.336	0.048
2002 EX12	2.603	0.767	0.606	11.3	34.2	2.887	
α Capricornids	2.565	0.770	0.590	7.0	36.0	2.917	0.050

4. Statistical Significance

Though an asteroid orbit lies near that of a minor shower, their proximity might simply be a coincidence. What is the probability that the orbit of an asteroid will, by chance, lie near that of a meteor shower? This depends on the distribution of asteroid orbits in the vicinity of the shower orbit. Particularly near the ecliptic, the possibility of a chance alignment is significant.

Given a potential asteroid–shower combination differing by D'_0, we can ask, how many other asteroids have $D' < D'_0$? If this number is large, the probability of a mere chance association is large. If the number is zero, we can still ask the question: given a distribution Y of N asteroids, what is the probability that a random selection from Y would have resulted in an asteroid closer to the shower than our chosen asteroid (i.e. that our randomly chosen asteroid has $D' \leq D'_0$)?

To answer this question, we turn to Monte Carlo techniques. We choose asteroids at random from the de-biased distribution of asteroid orbits (described below) until we select one that has $D' \leq D'_0$. The number n of trials required to do so provides a measure of the probability of a chance association. This procedure is repeated one hundred times and we consider the average number of trials $\langle n \rangle$. We define expectation value of the number of asteroids closer to the shower orbit than our test asteroid to be $P = N/\langle n \rangle$. If this number is much greater than one, then more than one asteroid is at least as well aligned with the shower as our test asteroid, and so a chance alignment becomes more probable. If this number is less than one, P represents the probability that another asteroid is closer to the shower than our chosen asteroid. A small value of P implies there are few other asteroids in the phase space around the shower, and thus that a chance alignment is unlikely.

Of course, even if the probability of a chance association is high, this does not exclude the existence of a real association between the stream and the asteroid. Nevertheless, it gives us a measure of whether an association is likely to be coincidental or not (assuming the stream is young, much less than a precession cycle in age).

Here we make use of the de-biased NEA distribution as determined by Bottke et al. (2002). From an examination of the Spacewatch program discoveries and recoveries and knowing the biases and sensitivities of the survey, they extrapolated from the observed distribution of NEAs to the real one. It is that distribution that we use here as a basis for estimating the probability P_d, where the subscript indicates we are using the de-biased distribution. We also compute the probability P_0 on the basis that the observed distribution is in fact the real one, as a secondary check.

Table II lists the results obtained for two previous shower–asteroid associations. The link between the Geminids and Phaethon ($D'_0 = 0.018$) is

TABLE II

Two previous associations of meteor showers (Cook, 1973) with asteroids (Whipple, 1983; Hasegawa, 2001)

	a	e	q	i	ϖ	T_j	P_0	P_d
Geminids	1.36	0.896	0.142	23.6	225.3	4.23		
3200 Phaethon	1.271	0.890	0.140	22.2	227.4	4.51	0.00014	0.00065
α Capricornids	2.53	0.77	0.59	7	36	2.94		
2101 Adonis	1.874	0.765	0.441	1.35	33.0	3.55	13	85

A value of $P > 1$ indicates the number of objects with $D' \leq D'_0$. See the text for details.

found to be extremely unlikely to be a mere chance alignment. However, the α Capricornids and 2101 Adonis ($D'_0 = 0.16$) are much more likely to be only coincidentally aligned, as there are 13 objects observed to have lower D' relative to that shower than Adonis, and the de-biased distribution predicts that there may be as many as 85 with smaller D' ultimately found.

For those possible associations mentioned earlier we find that for the α Bootids–2004 HA1 ($D'_0 = 0.028$) pair, $P_0 \approx 0.001$ and $P_d \approx 0.012$; for σ Leonids–1998 SH2 ($D'_0 = 0.047$), $P_0 \approx 0.19$, $P_d \approx 0.5$ and for the α Capricornids–2002 EX12 ($D'_0 = 0.051$), $P_0 \approx 0.069$ and $P_d \approx 0.3$. That means that (based on the de-biased distribution) there is a 1 in 83 chance that there is another asteroid closer to the α Bootids than 2004 HA1, a 1 in 2 chance that there is an asteroid closer to the σ Leonids than 1998 SH2, and a 1 in 3 chance for a better match than 2002 EX12 to the α Capricornids.

As a caveat, we note that this approach depends to a large extent on the stream orbit being well-known, which is not usually the case for weak showers. We will need to refine this work with improved stream orbits, which can be extracted from the CMOR orbit data set. We plan to do so by constructing a phase space density from the CMOR data set using the techniques of Welch (2001). This procedure converts the distribution of discrete orbits into a continuous distribution. It is then a simple matter to determine the locations of the density peaks near meteor showers, these peaks corresponding presumably to the best-fit orbit for the shower as a whole. Also needed is a consideration of the de-biased comet distribution. The probabilities computed above do not allow for the possibility that the source body is a comet and this will affect the computed statistical significance of any association.

5. Conclusions

Linking weak showers to their parents can be done with confidence given a sufficiently complete set of meteor orbits and near-Earth objects. A procedure which includes three tests is discussed. First, Steel-type plots as a function of longitude of perihelion allow the sporadic background to be assessed. Second, the D' parameter allows the nearness of a body's orbit to that of a shower to be determined. Third, Monte Carlo simulations allow the statistical significance of any hypothetical associations to be examined. The convergence of several different lines of evidence, each unconvincing on its own, allows stronger conclusions to be made. We also note that the existence of certain minor meteor showers has yet to be shown conclusively and it is hoped that the large CMOR dataset, with sensitivity at larger masses where showers are highly visible, will help remove some of this uncertainty.

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