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METEOR OUTBURSTS FROM LONG-PERIOD COMET DUST TRAILS

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ABSTRACT

Long-period comets have narrow 1-revolution old dust trails that can cause meteor outbursts when encountered by Earth. To facilitate observing campaigns that will characterise and perhaps help find Earth threatening long-period comets from their trace of meteoric debris, we use past accounts of outbursts from 14 different showers to calculate the future dust trail positions near Earth orbit. We also examine known near-Earth long-period comets and identify six potential new showers, which can be utilised to learn more about these objects. We demonstrate that it is the 1-revolution trail that is responsible for meteor outbursts. A method is presented that calculates in what year these showers are likely to return and at what hour. The calculations improve on earlier approximate methods that used the Sun's reflex motion to gauge the trail motion relative to Earth's orbit.

1. INTRODUCTION

Freshly ejected comet dust grains travel in orbits with slightly different orbital period, thus returning back to perihelion at different times. The result is that a cloud of dust ejected near perihelion returns one orbit later as a thin dust trail (Plavec 1955, Kresák 1958; 1976). In 1983, the InfraRed Astronomical Satellite IRAS detected thermal emission of comet dust trails in the orbit of short-period comets (Davies et al. 1984, Sykes et al. 1986, 1990). In recent years, it has become clear that Earth-threatening long-period comets with orbital periods of order 200 to 10,000 years can have associated dust trail too, which betray the comet's presence by causing short-lived outbursts of meteors (Kresák 1993, Jenniskens 1995), but only when that trail of dust is directed in Earth's path by planetary perturbations (Lewin 1961, Jenniskens et al. 1997, Jenniskens 1998).

Fourteen such meteor outbursts are known, mostly from anecdotes, some of which lack confirmation (Jenniskens 1995, Jenniskens et al. 1997). In only two of these cases do we know the parent comet: the *April Lyrids* had intense outbursts of meteors on April 20-22 1803, 1922 and 1982 and are associated with comet C/1861 G1 (Thatcher) with an orbital period of about 400 years; while the *θ–Aurigid* shower peaked on Aug. 31/Sept 01 in 1935, 1986 and 1994, and originates from comet C/1911 N1 (Kiess) with an orbital period of about 2000 years. These two comets are exceptional only because they approach Earth orbit close enough and their dust has not spread too thin.

In a previous paper, Jenniskens (1997) demonstrated that these outbursts tend to occur when the Sun's position relative to the barycenter of the solar system is about the same as during a prior event. It was postulated that the Sun's reflex motion might be a mirror image of the wanderings of a dust trail relative to Earth orbit as a result of planetary perturbations acting differently on grains at different mean anomaly. This hypothesis was used to predict the return of the *alpha-Monocerotid* shower on November 22, 1995, a shower that was seen earlier in 1925, 1935 and 1985 (Jenniskens 1995a). The outburst occurred as predicted, with a peak rate of 5/minute. It was the first such event observed by modern triangulation techniques. It was found that the meteoroids do not have a 10-year orbit as thought before (Rendtel et al. 1996, see also Arter & Williams 1997), but rather a long-period orbit ($P >> 150$ year), consistent with the wandering dust trail hypothesis (Jenniskens 1995a, Jenniskens et al. 1997).

That model is now tested further by calculating the dust trail position using tools developed to successfully predict past *Leonid* and *Ursid* outbursts from Halley-type comets (Lyytinen 1999, Lyytinen and Van Flandern 2000, Lyytinen et al. 2001, Jenniskens et al. 2002). The current paper differs from this prior work in that it considers comets with long enough orbital periods to not be trapped in mean-motion resonances (Chambers 1997). It is found that the position of a one-revolution dust trail can be calculated with sufficient precision to improve predictions of future encounters. A working list of such events has been compiled, which can help in gathering more information about the orbit and mass loss of their parent.

2. METHODS

The approach is to calculate the planetary perturbations on a series of particles ejected at a given perihelion return of the comet, for a range of orbital periods that will bring the meteoroids back to Earth orbit in the time frame of interest. Initial conditions are assumed to be as simple as possible, with dust release at perihelion only and with negligible speed (Lyytinen 1999, Lyytinen & Van Flandern 2000, Lyytinen et al. 2001). Radiation pressure on the grains is assumed to be responsible for the spread in orbital periods. Others have assumed non-negligible ejection in forward direction compared to the comet motion, with nearly identical results because the same difference in orbital period is needed to match the time of the shower with the perihelion time of the comet (Kondrat'eva & Reznikov 1985, McNaught & Asher 1999).

Unfortunately, even in the case of C/1861 G1 (Thatcher) the previous perihelion time is uncertain at best by a big fraction of the planet Jupiter's orbital period. Moreover, radiation pressure effects are uncertain enough (because we know little about the density and shape of the dust particles) to cause an ambiguity between, for example, one-revolution trails and two-revolution trails with half the orbital period. Without precise information about the perihelion time, one can not accurately predict the behaviour of the 2-revolution and older trails that tend to cause the outbursts of Halley-type comets.

The situation is even grimmer when only accounts of past meteor outbursts are available. In that case, only the node of the meteoroid orbit (time of the shower peak) and a radiant position is available. The radiant vector is defined as the opposite of the meteoroid velocity vector at Earth. If the speed itself can be measured, it is usually not precise enough to provide more than a lower limit to the orbital period. There are also considerable uncertainties in the radiant position when based on only visual observations, up to at least $\pm 8^{o}$ in some cases (Jenniskens et al. 1997). Furthermore, the Earth may not have passed through the centre of the dust trail, which creates an error in the initial orbital elements to be integrated backward in time.

We will now demonstrate that it is the one-revolution trail that is likely responsible for the observed outbursts, and the time of perihelion passage in the prior return does not need to be known precisely to predict where the new dust trail is going to cross the ecliptic plane.

Our approach is to integrate backward the orbit of an observed meteoroid or long-period comet for an assumed semi-major axis a (which, of course, relates to orbital period as: a, AU = P $^{2/3}$, yr), until one complete revolution to the previous perihelion passage, and adopt the thus found perihelion time as the time of ejection. The numerical integrator is of our own design and tested against, amongst others, the K11 orbit integrator version 3.0 by Christian Clowinski (Jenniskens et al. 2002). A time step of 0.5 days was chosen for the meteoroids, while the outer planet orbits were integrated in steps of 2 days. The current epoch is selected a few days prior to the observed outburst in order not to have to deal with a close Earth encounter in the backward integration. We then calculate the orbit of a series of particles, released at this time and place, for a small range of orbital periods. The orbital periods are chosen such that the particles trace the position of the comet dust trail near Earth orbit one revolution later over a time span from the first reported outbursts until at least the year 2050. Hence, the hypothetical meteoroid derived from the radiant of a past outburst will return at Earth's orbit again at the time of that outburst. Particles with slightly different orbital periods will return at different times, in a continuous manner, emanating from the position of the initial outburst. A constant increment in the ratio of radiation pressure over gravity β is chosen to create a series of orbital periods, small enough to trace the trail position after one revolution at Earth's orbit to within 0.0001 AU at the time of a potential outburst. The magnitude or distribution of this parameter is not important, as long as the interpolation for any outburst date can be performed reliably for all years in the period of interest. Orbits for different semi-major axis were calculated by adjusting the eccentricity and perihelion distance, with the angular elements left unchanged, so that each orbit continued to intersect the Earth's orbit at the time of the outburst.

3. RESULTS

The α-Monocerotids

Figure 1 shows the dust trail position at various times in the case of the *alpha-Monocerotids*. The vertical axis gives the distance from dust trail to Earth orbit for the ecliptic plane of date crossing of each particle. The initial orbit at the onset of the backward integration was calculated from the measured radiant position of the shower in November of 1995 (Jenniskens et al. 1997). To test the dependence on the semi-major axis, we selected the values a = 50, 100, and 500 AU, and calculated for each the corresponding dust trail. Note that the observed position of the trail at the time of return of the particle is not much affected by the assumed semi-major axis (that is, the prior perihelion time), but the effect is also not negligible (Lyytinen 1995).

We can now interpolate between calculated particle returns to find the position of the dust trail when Earth encounters the stream. Figure 2 shows the situation for the *alpha-Monocerotid* shower for two cases with a = 50 and 100 AU. The size of the symbols shows the dimension of the dust trail along the nodal line, assuming circle symmetry, and is proportional to twice the Full-Width-at-Half-Maximum of the dust trail as measured from the stream cross section (allowing for the Earth's oblique trajectory through the trail). The two examples show how much the calculated trail positions differ for assumed a = 50 and a = 100 AU.

Figure 3 shows the 2nd revolution old trail of the *alpha-Monocerotids.* Now, the exact result is valid only for the assumed time of perihelion passage of the comet, but it demonstrates that the cohesion of the trail quickly disappears. The dust is dispersed over such a large volume of space that such 2nd revolution old trails are not easily recognised. This is, because when the meteoroids make their first independent pass through the inner solar system, their orbital periods are changed by several times the 12 yr orbital period of Jupiter, and particles catch up on others from an initially quite different position in the trail. The trail forms loops that intersect in the dimension along the comet orbit. The new structure has a FWHM of about 0.02 AU (corresponding to an exponent B ~ 0.7 if the dust density is distributed ~ $10^{-B\,\Delta\Omega}$), the same as a stream structure known from Halley-type comets called the "Filament" (Jenniskens et al. 1998, Asher et al. 1999). Rather than of order one hour, it will take about a day to cross a Filament.

We conclude that only the one-revolution trails can account for the observed 40 minute long *alpha-Monocerotid* outbursts. The best solution appears to be a = 75 ± 5 AU (P = 650 yr), which would put all recent outbursts in Earth's path. Note that this orbital period defines the previous perihelion passage of the comet, but it is the orbital period of the meteoroids rather than that of the parent comet.

The April Lyrids

The *April Lyrids, alpha-Monocerotids,* and *theta-Aurigids* are known to have annual showers (Jenniskens 1994). Annual showers are also known from long period comets such as the parent of the *epsilon-Geminids,* for example, even though the one revolution trails can not presently cross the Earth orbit. A particularly nice study of the *April Lyrid* annual shower is given recently by Dubietis and Arlt (2000). The shower width is similar to that of the peak of the annual Perseid shower (Jenniskens 1994). In both cases, the annual shower is likely composed of particles that had close encounters with the major planets, but in the case of long-period comets secular perturbations may be responsible as well.

In the case of the *April Lyrids*, with relatively short orbital period, some structure of a 2-revolution train may perhaps even be recognised. The calculated positions of the one-revolution trail are shown in Figure 4. In this case, we used the known comet orbit as a starting point and plot the wanderings of the trail in the plane of the ecliptic. Most of the time, the dust trail is inside of Earth's orbit, but on occasion the trail is perturbed far enough outward to be in Earth's path. The agreement with observed outbursts is excellent. No past outbursts have been missed since 1803. Outbursts have been observed at least 58 yr before and up to 120 yr behind the comet's return in 1861. The 1922 and 1982 outbursts occurred only 6±6 and 9±3 minutes earlier than calculated. The next *April Lyrid* outburst is expected in 2040, and the intensity of the shower will provide information on how quickly the dust density falls off away from the comet position.

Knowing how far Earth passed from the centre of the dust trails in each encounter enables us to use the observed intensity of the showers to trace how quickly the dust falls off in the direction perpendicular to Earth's orbit. We simply assume that the dust disperses so rapidly, that the density is constant along the trail ±120 years from the comet position in this case. Figure 5 shows how the reported peak density (in terms of Zenith Hourly Rate) falls off away from the trail centre. The dust trail density distribution appears to be cylindrically symmetric, spread out as much in the plane of the comet orbit than along Earth orbit. The observations are well described by an exponential curve with peak ZHR = 1100±200 /hr and an exponent B = 33 per degree, equal to the dust distribution in Earth's path (Jenniskens 2001). Similarly, a Lorentz profile with full-width at half-maximum W = 0.00040 AU and ZHR max = 900 match the results (shown).

Lesser *April Lyrid* outbursts have also been reported, but are not well documented (Guth 1947, Emel'yanenko 1991). There are no activity curves of any of these events that trace the variation of activity. That leaves open the possibility that some, or all, are merely the results of better than usual observing conditions. On the other hand, many of these reports coincide with the trail being relatively close to Earth's orbit (grey circles in Figure 5). We conclude that, with the possible exception of the 1863 return, all other reported events are not part of the same one-revolution old dust trail and may outline the contour of either the *Lyrid* Filament or a 2-revolution (and later) old trail.

The θ–Aurigids

The *theta-Aurigids* case is the other known example where the comet orbit is known and several outbursts have been observed. The given orbit of the parent C/1911 N1 (Kiess), with P ~ 2000 yr., was adopted for determining the time of ejection. Now, we find that the calculated trail positions tend to lie systematically inside of Earth's orbit (Figure 6). It is possible that in all cases the Earth did not cross the centre of the dust trail (open symbols in Figure 5 match the observed peak rates to the Lyrid profile, for example). However, also the predicted times of the showers are significantly earlier than calculated: -19±3 min. (1986) and -57±7 min (1994). We find that uncertainties in the comet orbit itself can not account for the large discrepancy in 1994, but leave open the possibility that particulars of the ejection process may be responsible.

The next *θ-Aurigid* outburst is due in 2007, and is expected to be a spectacularly rich shower of bright +0 to +2 magnitude meteors (Jenniskens 1997).

4. APPLICATION TO OTHER SHOWERS

The prior examples demonstrate that future returns from encounters with the one-revolution trail can be calculated if one throws a wide enough net to account for the unknown time of ejection and accepts up to 1 hour uncertainty in the encounter time. A working list of probable (shown in bold) or possible returns in the next 50 years is given in Table I. Probable returns are those for which the trail position is calculated to be in Earth's path. In many cases, however, there are significant uncertainties that warrant a closer inspection, which will be discussed now.

The return of past meteor outbursts

Apart from the three showers discussed before, there are only 11 known outbursts that are not associated with the return of a comet to perihelion, all of which were seen only once (Jenniskens 1995; 1997, Jenniskens et al. 1997). Among those "far-comet type" outbursts, the following showers are well documented by numerous observers: the *α-Hydrusids* (aHy), the *κ-Pavonids* (kPa), and the *α-Centaurids* (aCe). Two other showers, the *β-Perseids* (bPe) and *α-Bootids* (aBo), were reportedly very rich showers of faint meteors, but they lack confirmation from an independent observer. From our calculations, we make two post-predictions for the *β-Perseids* for 1946 (Aug. 07, 18:08 UT) and 1971 (Aug. 08, 04:24 UT). The remaining six showers, the *α-Lyncids* (aLy), the *α-Pyxisids* (aPx), the *o-Orionids* (oOr), the *ε-Eridanids* (eEr), the *γ-Delphinids* (gDe), and the *α-Circinids* (aCi) are less well documented (Jenniskens 1995, Jenniskens et al. 1997). Future returns need to establish that these are indeed long-period comet dust trail encounters.

The first complication is that possible errors in the reported radiant position can introduce large variations in the calculated trail positions because of relatively close encounters with one of the outer planets. Figure 7 shows the case of the *alpha Centaurids*. If the radiant right ascension is uncertain by as much as +9.5 degrees, then there are sufficiently close encounters with Jupiter to severely distort the dust trails every 12 years. That would suddenly make outbursts possible in 2014 and 2015, years that would not be considered otherwise. However, even in this case it is still possible to identify which years are the more promising for the return of a shower, and are marked "RA+" in Table I. Moreover, the outbursts (if any) are expected within an hour from the given time, which should greatly facilitate observing campaigns.

These uncertainties are highly case specific and were studied by calculating independent trail positions for each stream with radiant positions +5 degree higher Declination and +5 to +10 degree higher Right Ascension. The nominal trail positions for other far-comet type outbursts are shown in Figure 8. In addition, Table I includes many possible encounters that are valid only in case of large errors in the radiant position. Such errors are known from past observations of the *alpha-Monocerotids*, for example.

Of particular interest is the *epsilon Eridanids* shower (Figure 9), tentatively associated with parent comet C/1854 L1 (Klinkerfuess). This comet has only known parabolic elements and may, or may not, be long period. Furthermore, the initial account of the shower implies that the *ε–Eridanids* are unusually broad (Jenniskens 1995). There is also a difference of more than one degree in the node between shower and comet orbit. We find that the one-revolution trail calculated from the comet elements does not cross the Earth orbit. It is possible that a 2-revolution old trail was observed that could account for the broadness. However, we can not check this possibility with the current modelling.

Showers from known long-period comets

The most likely sources of new showers are those long-period comets that come within 0.01 AU from Earth orbit and have orbital periods up to ~ 10,000 years. For a given mass loss, the dust density is proportional to $a^{-2.5}$ (Sykes et al. 1992). As an example, for a 5000 year orbital period, the density is about1/60 that of the *April Lyrid* trail. Because of this, no outbursts are expected from comets with periods over a few thousand years, except maybe from Hale-Bopp sized giants. We have examined all known near-Earth long-period comets (Marsden & Williams 1997, recent IAU circulars) and predicted possible dust trail crossings (Table I). We adopted the calculated semi-major axis if this had been calculated to be of order a few hundred AU. In other cases, we assumed an (arbitrary) initial semi-major axis a = 80 or a = 100 AU (Table I). In one case, for the comet C/2000 WM1 (LINEAR), the calculations were published elsewhere (Jenniskens & Lyytinen 2001). Despite its fairly close encounter with Earth's orbit, we calculated that no outburst was expected from this comet, and none was observed.

One additional complication in deciding whether a dust trail of a known comet passes close enough to Earth's orbit is to estimate the width of the dust trail. The width is a direct reflection of the ejection velocities at perihelion, a function of perihelion distance and the mass of the comet nucleus. As a first approximation for the width (W) of the shower, we used the Whipple equation for dust ejection by water vapour drag (Whipple 1951, as modified by Jones 1995) and the observed outbursts to derive an approximate lower limit: Log W (AU) = -3.97 - 0.6 log q (AU). In practise, W could be larger and we used the Lyrid W = 0.0008 AU as a reasonable upper limit.

The following are promising cases. A likely source of a meteor outburst on March 1 in 2003 is comet C/1976 D1 (Bradfield) with P ~ 1000 yr (Table I). It is a bit unfortunate that observing conditions will be bad. The shower has a very southern radiant and in a sun ward direction. The best viewing location is in the Southern Atlantic and parts of Eastern South-America in the evening sky. This outburst is also visible from South Africa with a low radiant elevation. The parent comet has lower intrinsic brightness than the *April Lyrids* and *Aurigids* parent comets.

The next encounters with the C/1907 G1 (Grigg-Mellish) trail are predicted from the comet's parabolic elements: in 2018, 2019 and 2043. The predictions are uncertain because they occur at a time when the trail positions change rapidly. This comet has an associated annual shower called the *delta-Pavonids*, but without known meteor outbursts. A post-prediction is made of a shower in 1935, March 31 at 04:20 UT.

Another possible source of outbursts is comet C/1854 R1 (Klinkerfuess), with an orbital period of P ~ 1100 yr. A trail encounter is predicted on February 15, 2035, but the event coincides with a particularly strong deviation of the dust trail outward from an encounter with Jupiter, which decreases chances that the trail position is exactly right at the time of encounter.

Similarly, two encounters are predicted with comet C/1969 T1 (Tago-Sato-Kosaka). The given orbital period of this comet is almost 90,000 years. If so, the trail is expected to have stretched very thin. A post prediction of an encounter at +0.0006 AU in 1999, Jan. 2 at 21:50 UT, was also derived, but can not be confirmed due to a general lack of radio forward meteor scatter observations on the southern hemisphere.

A 2021 encounter is predicted with the C/1852 K1 (Chacornac) trail at a distance of -0.0001 AU. Only a parabolic orbit is known, hence the trail length and density are unknown. A recent post predicted encounter was in 1997, Aug. 12 00:48 UT, at -0.0004 AU. This shower would have occurred at the peak of the Perseids, which will tend to saturate forward meteor scatter systems. No visual observations were reported.

C/1983 H1 (IRAS-Araki-Alcock) is a P ~ 1000 yr comet that has a known annual shower, the *eta-Lyrids* of May 10 (Jenniskens 1985). Indeed, four meteoroid orbits have been obtained from photographic records. However, 1983 encounter with Earth was very unusual in being one of its closest encounters possible. Calculations show that the comet dust trail will not come any closer to Earth orbit than about 0.005 AU in the next century.

5. DISCUSSION

Jenniskens (1995, 1997) successfully used the Sun's reflex motion as a means of predicting the position of the dust trails. We now confirm that there is surprisingly good agreement between the relative position of the comet dust trail to Earth's orbit and the position of the Sun relative to the barycenter in the same co-ordinate system, defined as:

$$\Delta(X,Y) = - \Sigma_i \frac{m_i}{(M_o + \Sigma_i m_i)} (X,Y)_i \qquad (1)$$

where the summation is over the 9 planets, m_i is the mass of the planet i, M_o the mass of the Sun, and R_i the heliocentric distance to planet i in the correct co-ordinate system (X,Y). Figure 10 shows the *alpha-Monocerotid* example. There is good agreement, except for a delay of 1.4±0.1 years in the motion along the nodal line, in which the dust trail lags the Sun's position. The parallel motion (solar longitude) is in phase. Note that Jenniskens (1997) found the same 1.5±0.3 year delay in the perpendicular position of the Perseid dust trail calculated by Wu & Williams (1993). Again, the parallel motion was in phase. We note that the delay in the pattern is the same as the 1.47 yr. it takes for the meteoroids to travel from perihelion to the nearest point with Jupiter's orbit.

Unlike the rigorous particle orbit computations presented here, the Sun's barycentric position can be derived from data in the Astronomical Almanac. The main drawback of this method is that the Sun's reflex motion does not take into account close encounters with the outer planets (e.g., Figure 7). A comparison with Table I shows that earlier predictions based on repetitions of the Sun's barycentric position are in general agreement with our new results, but many are off by 1 year and sometimes more.

The reason for the wagging motion of the dust trail relative to Earth's orbit is the planetary perturbations on the inward leg of the orbit. The meteoroids keep close to each other and to the parent comet while going outward on their first orbit. The meteoroids will get more separated only after leaving the planetary system, whereby those having longer orbital periods will move ahead of the pack. When well outside the planetary system, the particles move in ellipses with one focus at the barycenter of the solar system. This motion is quite close to Keplerian motion around a single body, with only little perturbations from the planets. This situation will be preserved until the meteoroids once again start to get near the Sun through the planetary system. Because the mean anomaly, or timing, of different meteoroids now differs very much, the perturbations will be quite different, reflecting the position of Jupiter relative to the meteoroid's orbital plane at a given time.

6. IMPLICATIONS

The new predictions intend to help observers gather information on the orbit, particle density, size distribution, and flux density in the known long-period comet dust trails. Accurate measurements of orbital elements can provide some protection against a potential impact. The 1803 outburst of the Lyrid shower is an example of how a meteor outburst preceded the return of the parent comet (in 1861).

The orbital elements of the grains in the dust trail resemble closely that of the parent comet, more so than the dust grains that make up the annual shower. Based on those orbital elements, one could keep a close watch on that dynamic region of the sky where such a potential impactor would be if it was going to hit Earth. The dust size distribution can help refine the orbital period of the grains, because an upper size mass limit appears to define what particles can be released in a bound orbit (Jenniskens et al. 1997). Moreover, the width of the shower profile and the measured particle density put constraints on the size of the parent body as shown by Jenniskens et al. (1997).

The orbital period of known long-period comets can perhaps also be improved by outburst observations. When the time of perihelion passage is known, the position of the trail in different encounters is a sensitive function of the orbital period. The dispersion of the dust along the comet orbit will be a function of the initial orbital period as well. That will more accurately predict the return of an Earth threatening comet for future generations.

Many past outburst accounts are uncertain and even the detection of a few meteors from the shower in one of the possible returns in Table I may help constrain the dust trail models by defining the radiant more accurately and verifying the long orbital period. Even a non-detection is of value. In addition, many dust trails may exist that are not yet documented.

Informed witnesses of such surprise future meteor outbursts should go home with this message in their mind: the accuracy of the radiant position makes all the difference in predicting future occurrences. A precision of at least ±0.5 degrees is often needed to correctly address close encounters with the outer planets. This calls for the application of routine video observing or radar techniques to obtain accurate radiant positions.

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Table I

Working list of far-comet type meteor outbursts. Bold entries are the more certain predictions. Times can be uncertain by up to 1 hour, solar longitudes uncertain by up to 0.05°. Comments: "far" means large calculated distance from Earth orbit in nominal case; "barely" means calculated encounter is far from trail center; "RA+": only if radiant position off by up to 10 degrees; "steep": a rapid change of the trail position with time; "uncertain": rapid changes with radiant position. Name conventions follow the shower accounts in Jenniskens (1995, 1997): aBo = *alpha-Bootids*, aCe = *alpha-Centaurids*, aCi = *alpha-Circinids*, aLy = *alpha-Lyncids*, aMo = *alpha-Monocerotids*, aPx = *alpha-Pixiids*, bPe = *beta-Perseids*, bHy = *beta-Hydrusids*, eEr = *epsilon-Eridanids*, gDe = *gamma-Delphinids*, kPa = *kappa-Pavonids*, Lyrids = *April Lyrids*, oOr = *omicron-Orionids*, tAr = *theta-Aurigids*.

Date yr:mo:day (UT)	Name	Miss Distance (AU)	Radiant RA	DEC	Solar Longitude (J2000)	Comments
2003 02 08 09:07	aCe	-0.00081	210	-58	319.148	far, RA+
2003 03 01 21:54	**C/1976 D1**	**-0.00008**	**013**	**-64**	**340.861**	
2003 06 11 16:22	gDe	-0.00026	312	+17	080.300	barely
2004 02 07 16:00	aCe	-0.00102	210	-58	319.175	far, RA+
2004 09 11 18:01	eEr	+0.00127	056	-14	168.267	(if long period)
2005 08 07 20:11	bPe	<0.002	052	+40	135.332	uncertain
2006 01 02 06:21	**C/1969 T1**	**-0.00028**	**231**	**-57**	**281.633**	**barely**
2006 07 16 23:23	kPa	<0.0007	275	-67	114.189	uncertain
2006 08 08 02:50	bPe	+0.00019	052	+40	135.357	steep/faint meteors
2007 04 28 17:28	aBo	+0.00027	219	+19	037.954	faint meteors

2007 12 21 03:40	**aLy**	**-0.00011**	**138**	**+44**	**268.769**	
2008 12 20 08:10	aLy	+0.00040	138	44	268.691	RA+
2011 01 02 20:47	C/1969 T1	+0.00058	231	-57	281.952	too far?
2011 06 05 05:44	**aCi**	**-0.00001**	**218**	**-70**	**074.094**	
2012 06 04 10:43	aCi	+0.00027	218	-70	074.041	RA+
2012 11 26 09:47	oOr	+0.0011	085	+04	244.368	if RA+
2012 06 11 04:24	gDe	+0.00036	312	+17	080.484	barely
2013 06 11 08:28	**gDe**	**+0.00021**	**312**	**+17**	**080.402**	
2015 02 08 11:28	aCe	+0.00021	210	-58	319.161	rapid, RA+
2016 12 20 14:45	aLy	+0.00022	138	+44	268.922	if RA+
2018 03 31 11:47	C/1907 G1	-0.00048	309	-60	010.463	steep, far
2019 03 31 17:26	C/1907 G1	+0.00017	309	-60	010.444	steep
2019 08 17 03:19	bHy	-0.00046	023	-76	143.693	too far?
2019 11 22 04:52	aMo	-0.00036	117	+01	239.306	far
2020 08 16 14:18	**bHy**	**+0.00027**	**023**	**-76**	**143.886**	
2021 03 01 09:32	C/1976 D1	-0.00035	013	-64	340.729	too far?
2021 08 12 04:22	**C/1852 K1**	**-0.00010**	**043**	**-13**	**139.402**	
2022 08 12 11:59	C/1852 K1	-0.00040	043	-13	139.465	
2027 06 11 21:55	**gDe**	**+0.00010**	**312**	**+17**	**080.378**	
2029 08 07 23:33	bPe	<0.0003	052	+40	135.319	uncertain
2030 07 17 03:33	kPa	<0.001	275	-67	114.211	uncertain
2031 07 17 19:30	kPa	+0.00046	275	-67	114.600	RA+
2032 03 01 06:35	C/1976 D1	-0.00025	013	-64	340.789	
2033 06 05 00:32	**aCi**	**+0.00004**	**218**	**-70**	**074.229**	
2034 06 11 22:21	gDe	+0.00022	312	+17	080.591	too far?
2035 02 15 22:22	C/1854 R1	+0.00069	305	+38	326.574	far,steep
2035 11 27 02:32	oOr	+0.0004	085	+04	244.160	steep, far?
2037 06 04 19:18	aCi	-0.00031	218	-70	073.988	too far?
2038 03 01 21:46	C/1976 D1	-0.00011	013	-64	340.875	
2038 09 11 12:43	**eEr**	**+0.00031**	**056**	**-14**	**168.364**	**(if long period)**
2038 03 06 18:52	aPx	+0.00055	135	-35	345.767	too far?
2039 09 11 16:27	**eEr**	**-0.00054**	**056**	**-14**	**168.261**	**(if long period)**
2039 03 07 08:24	**aPx**	**+0.00009**	**135**	**-35**	**346.074**	
2039 02 08 15:28	**aCe**	**+0.00036**	**210**	**-58**	**319.174**	**too far?**
2040 09 10 20:25	**eEr**	**-0.00009**	**056**	**-14**	**168.172**	**(if long period)**
2040 04 22 00:25	**Lyrids**	**-0.00022**	**271**	**+34**	**031.942**	**faint meteors**
2041 04 22 08:40	**Lyrids**	**-0.00025**	**271**	**+34**	**032.022**	**faint meteors**
2042 03 31 15:58	C/1907 G1	-0.00026	309	-60	010.484	steep
2043 11 22 10:58	**aMo**	**-0.00008**	**117**	**+01**	**239.409**	
2043 03 31 21:36	**C/1907 G1**	**-0.00005**	**309**	**-60**	**010.464**	
2044 03 31 03:16	C/1907 G1	+0.00016	309	-60	010.446	steep
2045 03 31 09:13	C/1907 G1	+0.00013	309	-60	010.436	steep
2048 03 31 15:45	C/1907 G1	-0.00039	309	-60	010.448	steep
2048 06 11 09:48	gDe	+0.00013	312	+17	080.484	
2049 06 11 14:02	gDe	+0.00023	312	+17	080.407	
2050 03 01 22:52	C/1976 D1	-0.00011	013	-64	340.846	

FIGURES

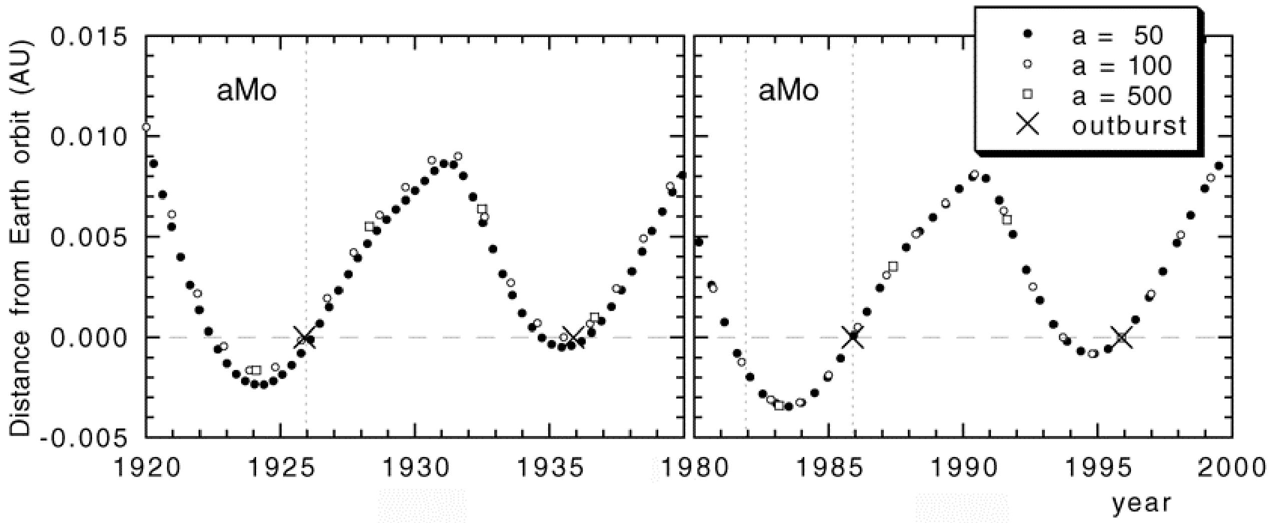

Figure 1 - The position of the α–*Monocerotid* dust trail near Earth orbit as a function of the time when particles return to the node. Each point marks a single particle in the calculation. Different symbols represent initial orbits with assumed semi-major axis a = 50 (•), 100 (o), or 500 AU. Crosses mark when α–*Monocerotid* outbursts were observed.

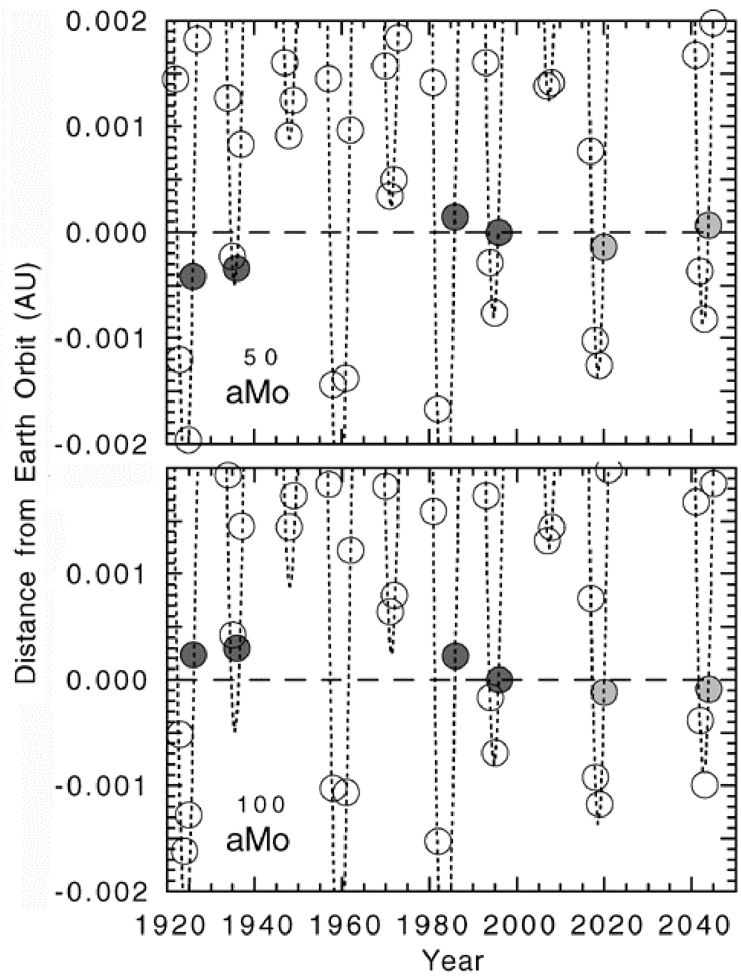

Figure 2 - Position of the *α–Monocerotid* dust trail on November 22 in a given year. Dark circles show the years of confirmed meteor outbursts. Grey circles are favorable encounters in the future. The vertical size of the symbols is proportional to twice the stream width measured in the path of the Earth. The two parts of the figure show how the pattern changes when the semi-major axis is changed from 50 AU (top) to 100 AU (bottom).

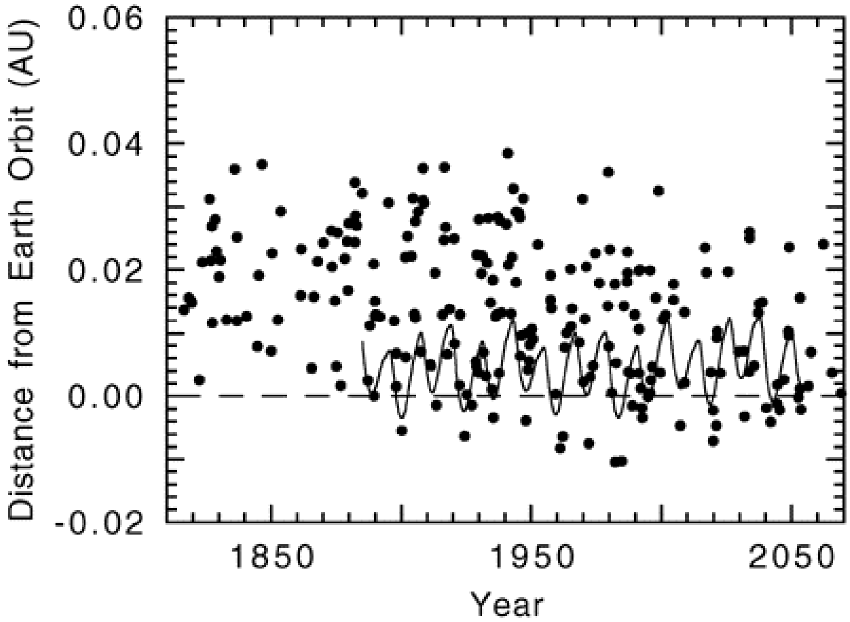

Figure 3 - As Figure 1. The general distribution of ecliptic-plane crossings for a two revolution old dust trail (points) compared to a one-revolution trail (solid line).

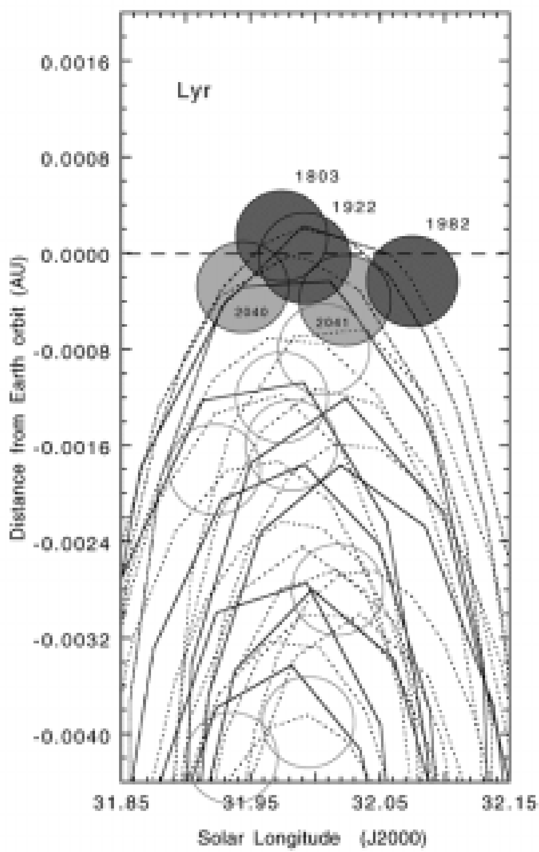

Figure 4 - The one-revolution dust trail of comet Thatcher as it moves in the ecliptic plane. Dashed lines for past encounters and solid lines for future encounters show the circular patterns from the 12-year orbital period of Jupiter. The jagged motion is an effect of limited resolution in the calculations. Circles show the position of the dust trail during the observed *April Lyrid* meteor outbursts as in Fig. 2.

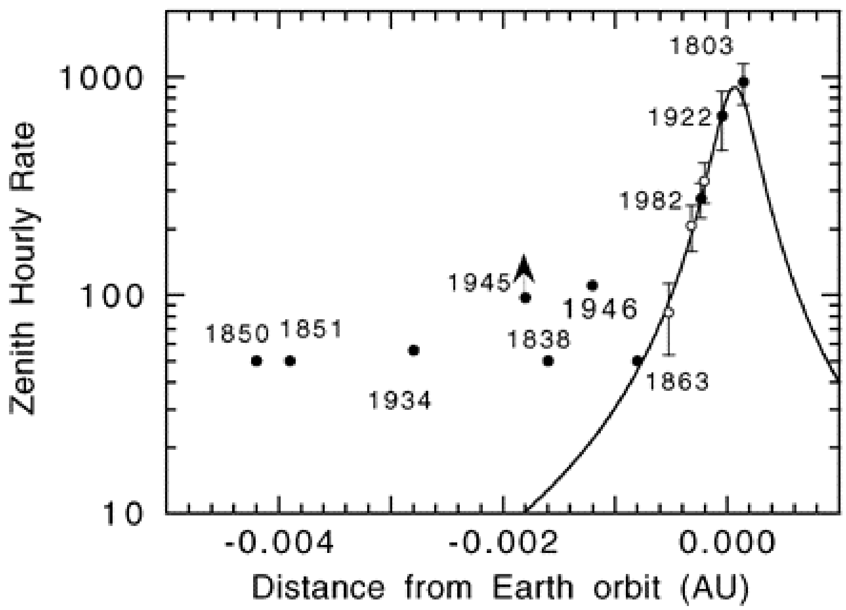

Figure 5 - Variation of *April Lyrid* shower peak rates (•) (Guth 1947, Jenniskens 1995) as a function of the calculated 1-revolution dust trail position. Open symbols are similar results for the *theta- Aurigids*, vertically scaled to match the *Lyrid* profile.

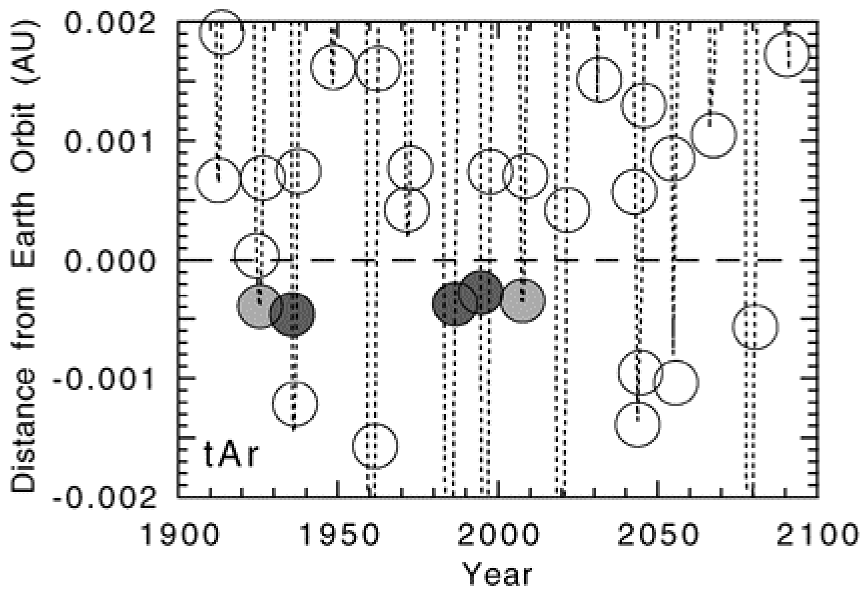

Figure 6 - Position of the *theta-Aurigid* dust trail on Aug. 31. Confirmed outbursts are shown as a circle (2 FWHM high). The next outburst is due in 2007.

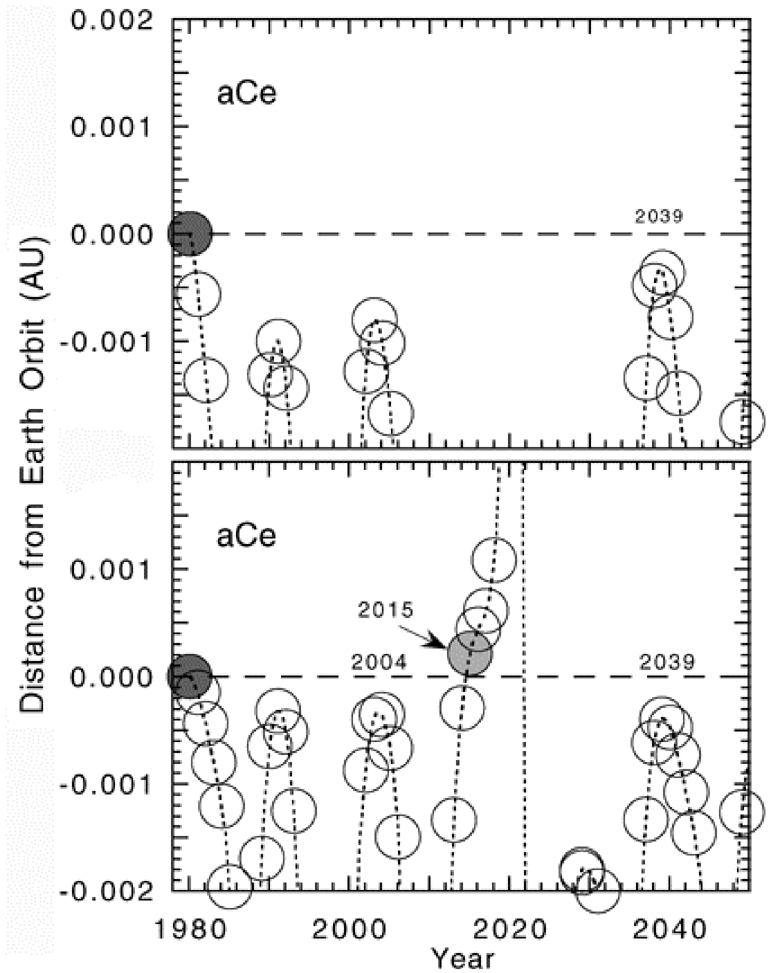

Figure 7 - *Alpha-Centaurid* shower trail position for the nominal radiant position (top), and for a radiant that is + 9.5 degrees higher in Right Ascension (bottom).

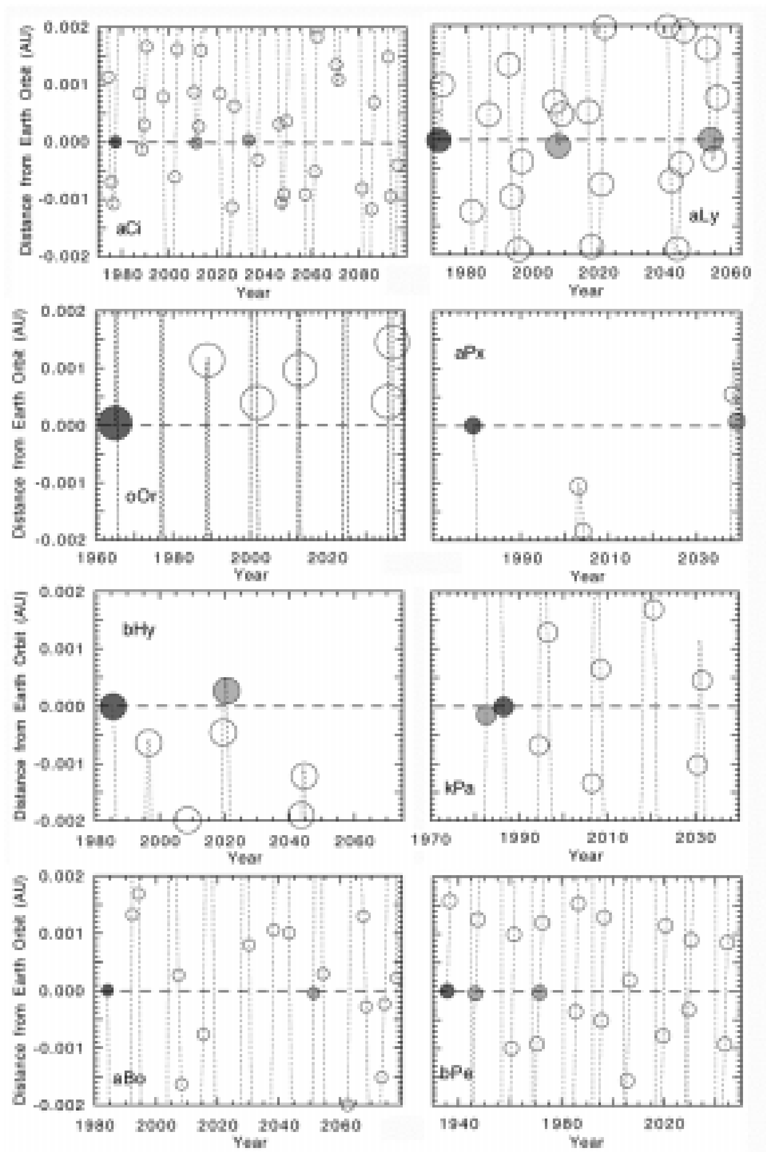

Figure 8 - The trail position of other suspected long-period comets based on meteor outburst observations. Stream nomenclature and abbreviations follow Jenniskens et al. (1997).

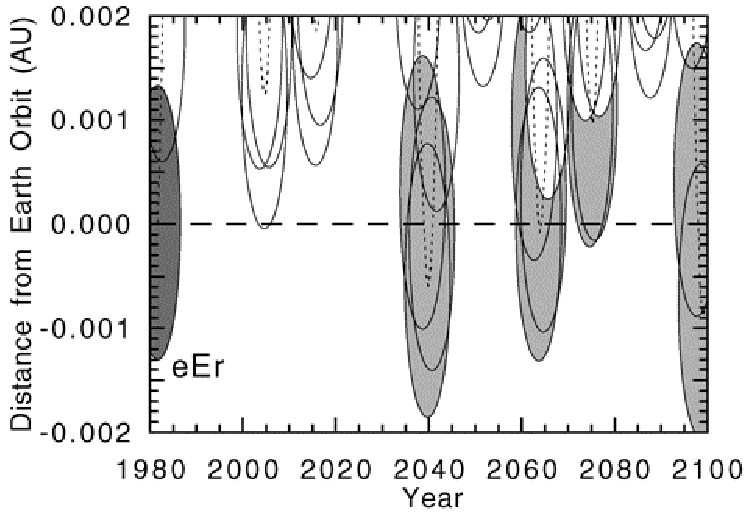

Figure 9 - As Fig. 8, for the *epsilon-Eridanid* shower.

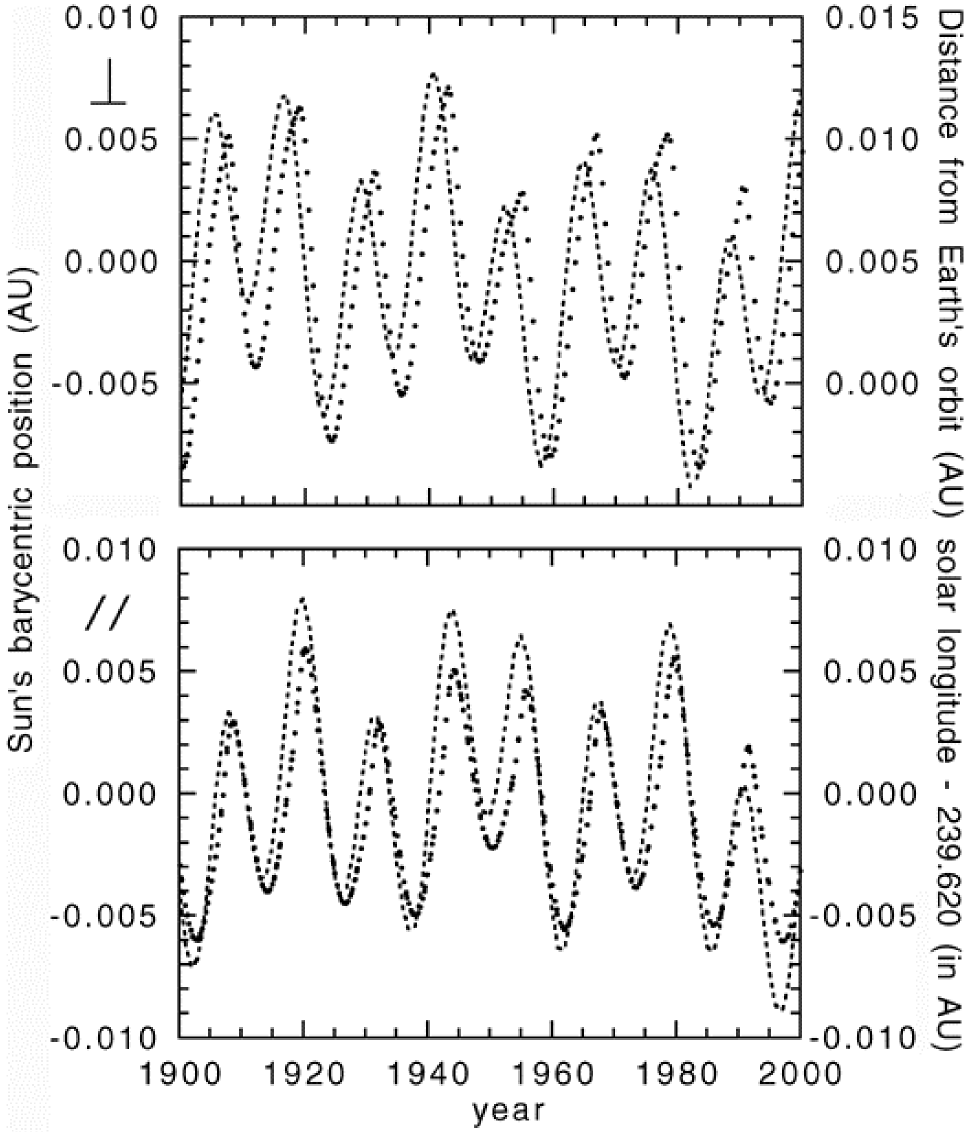

Figure 10 - The position of the Sun relative to the barycenter of the solar system (dashed line) and the calculated dust trail position for the *alpha-Monocerotid* shower relative to Earth's orbit in the same coordinate system. The two graphs show the position along the nodal line (left) and the position along Earth's orbit (right) on Nov. 22 of each year.