

Dynamics of Leonid dust trails (the cause of storms)

D.J. Asher

Armagh Observatory, Northern Ireland

(Last revised 2000 February 7)

Although the background level of meteors from the Leonid stream is not especially high, within the stream are dense, narrow trails of meteoroids and dust, the debris of Comet 55P/Tempel-Tuttle. These trails are similar to those discovered by the Infra-Red Astronomical Satellite in the orbits of other periodic comets. When the Earth encounters a trail, a meteor outburst or storm occurs. Two qualitatively different kinds of trail are present in the Leonid stream. ‘Normal’ trails, up to a few centuries old, form simply because meteoroid particles of slightly smaller and larger orbital periods than the comet gradually stretch ahead of and behind the comet. The number density of particles is much higher at the centre of these trails than elsewhere in the Leonid stream. Therefore the Earth’s passages close to the centre of these trails are associated with the highest Zenithal Hourly Rate storms. Trails of the second kind form as a result of resonant dynamical behaviour over more than a few centuries. Although the overall number densities of meteoroid particles in resonant trails are smaller than in normal trails, the resonant trails are rich in larger particles. This meant that the 1998 outburst had much lower ZHR than the greatest Leonid storms, but was rich in fireballs. The positions of both kinds of trail in space can be accurately calculated, by accounting for gravitational perturbations, allowing meteor storms to be predicted.

1 DYNAMICS OF YOUNG DUST TRAILS

Trail formation

Each time an active, periodic comet such as 55P/Tempel-Tuttle returns to perihelion, ices near the surface of the cometary nucleus sublimate, and the expanding gas drags small, solid particles (meteoroids and dust) away from the nucleus. The smallest particles are quickly swept into the comet’s dust *tail* by solar radiation pressure. Somewhat larger meteoroid particles, of a size capable of producing visual meteors (1 mm grains will give visual Leonids) are also acted on by radiation pressure (see below) but to a lesser degree. After being released from the nucleus, these particles are able to remain within the Leonid stream, which is basically a tube of meteoroidal material surrounding the comet orbit. The particles are not immediately scattered at random throughout the stream, and it is the structure within the stream, i.e., the existence of regions of higher and lower density, that causes variations in meteor activity.

As they escape from the cometary nucleus, the meteoroids possess some velocity, relative to the nucleus. This ejection velocity is probably of order tens of ms^{-1} for mm-sized particles, compared to $\sim 42 \text{ km s}^{-1}$ (at perihelion) for 55P/Tempel-Tuttle’s orbital velocity around the Sun. This small difference in velocity means that each meteoroid’s orbit is similar but not identical to the comet’s orbit. Immediately after ejection, therefore, particles’ orbits cover a range of orbital periods, concentrating towards 55P/Tempel-Tuttle’s period of ~ 33 yr. It is a simple consequence of orbital motion that

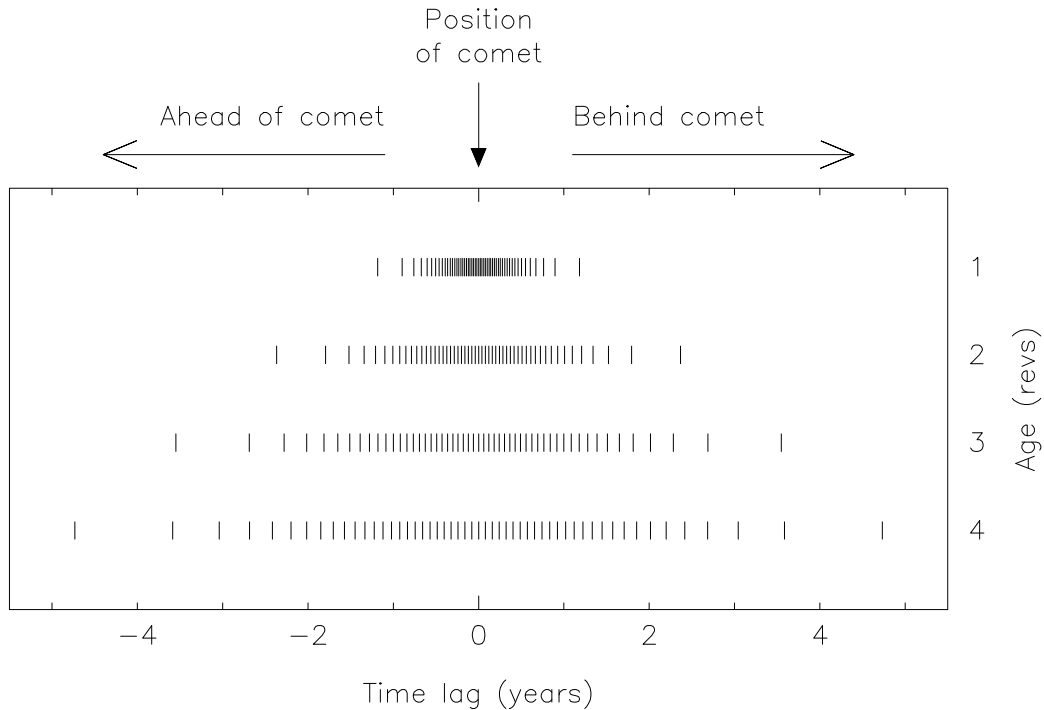


Figure 1. Evolution of a Leonid dust trail, shown after 1, 2, 3 and 4 revolutions, neglecting radiation pressure and gravitational perturbations. The x-axis is the time by which particles lead or follow the comet. In this representation, particle density in the trail is inversely proportional to spacing between lines. Two points to note are:

(i) At any one time, the density profile along the trail shows a concentration close to the comet. The extent of this concentration could be adjusted (compressed or expanded) depending on the assumed model of ejection from the comet nucleus (in general, smaller ejection velocities give a smaller range of meteoroids' orbital periods, and compress the concentration towards the comet more), but here is in reasonable accord with expected ejection velocities for particles in a Leonid trail that would produce visual meteors.

(ii) The density becomes diluted with time, since the separation between particles increases (any particle with a longer orbital period gets progressively further behind a particle whose period is shorter). In this approximation of no gravitational perturbations, the trail necessarily lengthens at a constant rate.

particles with smaller and larger periods will progressively get ahead and fall behind respectively. The result is elongation into a *trail*, whose length increases with time as particles stretch further ahead and behind (Fig. 1).

Solar radiation falling on meteoroid particles exerts a force on them. Radiation pressure varies inversely with the square of the distance from the Sun, as does Newtonian gravity, but acting in the opposite direction. Any given particle therefore orbits the Sun on an ellipse, as it would if subject to solar gravity alone, but with the inverse square force reduced by a constant fraction. Effectively, the Sun pulls the particle around its orbit less strongly, and so an orbital revolution takes longer to complete. This means that dust trails tend to be shifted backwards relative to the comet. The size of the radiation pressure force varies with the sizes and densities of particles, being greater,

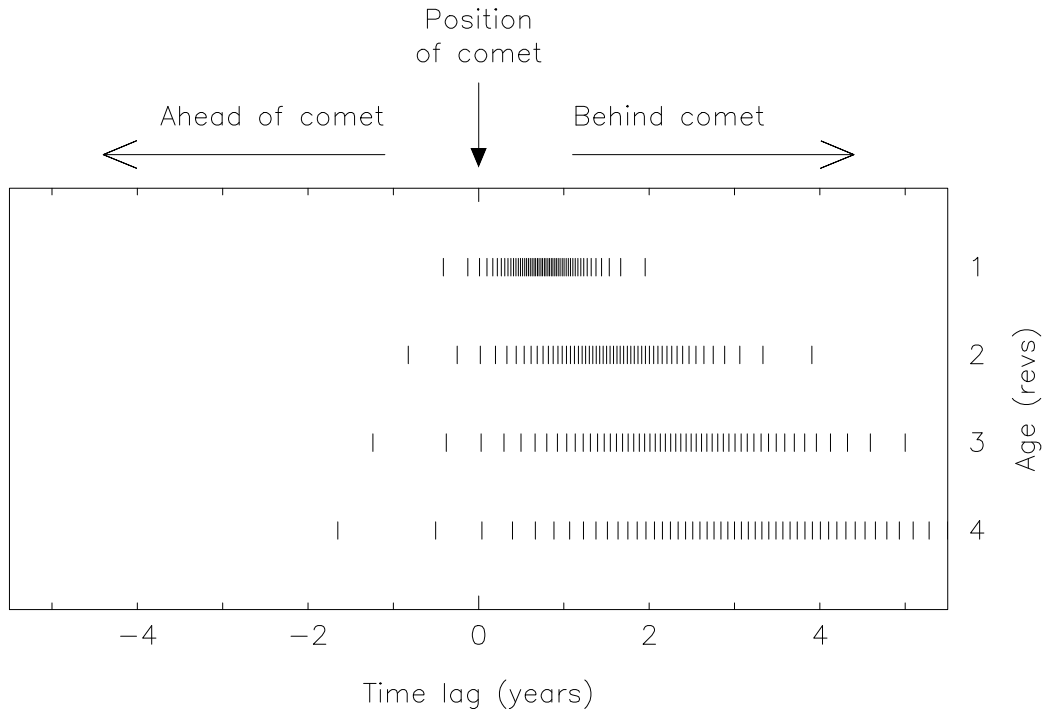


Figure 2. Evolution of a Leonid dust trail, shown after 1, 2, 3 and 4 revolutions, neglecting gravitational perturbations, but allowing for radiation pressure at a suitable average value for particles that produce visual meteors. Cf. Fig.1.

as a fraction of solar gravity, for smaller particles. The effect on a dust trail for a single value of the radiation pressure parameter, that can reasonably be expected to correspond to visual meteors, is illustrated in Fig. 2.

The above discussion was of the density profile *along* a trail. Evidently the density also varies *across* the trail. Expected ejection velocities, based on current knowledge of meteoroid ejection processes from comets, imply that mm-sized particles in a trail are contained within a cross section whose width is of order ten Earth diameters at 1 astronomical unit from the Sun. Moreover, as intuitively expected, the density profile increases sharply towards the nominal centre of the trail. Radiation pressure increases the cross section, but not substantially for these particles. As this cross section is very narrow on the scale of the whole Leonid stream, the chance of the Earth encountering the core of any one trail, on a random passage through the stream, is quite small. But dynamical calculations can make such statements about particular trails definite, rather than based on chance.

Evolution under planetary perturbations

Dust trails evolve through the gravitational perturbations of the planets. One consequence is that the rate of lengthening (cf. point (ii) in Fig. 1 caption) is different at different points along a trail. This effect can be accurately evaluated using a computer program that takes account of the planets. In practice, for the first couple of revolutions, the density profile along a trail evolves as shown schematically in Figs 1 & 2, gradually starting to deviate thereafter.

However, the most important effect of planetary perturbations is that they can shift the orbits of dust trail particles towards or away from the Earth's orbit. As these shifts are often by distances much greater than a trail's width, they can make the difference between having a spectacular meteor storm, or no outburst at all.

Even after less than one revolution, trails are long enough that perturbations vary greatly along the trail. For example, one part of a trail may at some time be significantly nearer Jupiter than another, and therefore get shifted significantly more by the planet's gravity than the part of the trail that is further away. The other side of this argument is that particles a similar distance along a single trail, i.e., that are approximately comoving, undergo the same perturbations, and so do not disperse relative to each other. Thus *all* the particles in one part of a trail can be shifted to bring them nearer to or further from the Earth's orbit, but they do not shift *relative to each other*, and the trail's cross section at any one point does not become wider with each successive revolution (dynamical simulations show this to be true for a few centuries).

Just as they shift particle orbits, perturbations continuously shift the comet's orbit, and the comet returns to a slightly different point at each successive perihelion. This means that each new dust trail, arising from the material released during one perihelion return, begins in a slightly different position from previous trails. Additionally, the configuration of the planets changes every ~ 33 yr. It follows that every trail's dynamical evolution is unique, and must be calculated individually, using the computer program that evaluates planetary perturbations. It is also clear that separated trails, generated at ~ 33 yr intervals, do indeed exist, rather than all trails coinciding around a single orbit. The dust trail structure of the stream may be thought of as multiple, dense, narrow strands, flowing through the Leonid stream as a whole, diverging from the comet both in front, and (mostly) behind. No trail lies exactly along an elliptical orbit.

Ecliptic crossings

As perturbations vary along a trail, they must be calculated for the parts of each trail that are of interest. For the purpose of predicting meteor activity, the relevant parts of the trails are those that pass through the plane of the Earth's orbit, from north to south, in mid-November of each year. Fig. 2 shows that a trail can soon lengthen sufficiently that the front is some years ahead of the back, and successive sections (of reasonable density) of the same trail can reach the ecliptic in quite a few consecutive mid-Novembers. A computer program can be used to calculate the dynamical evolution of these parts of trails, from the time when particles are released from the comet until the time (mid-November of some year) when they reach the ecliptic, and to specify the point where each trail section crosses the ecliptic. The closeness of these crossing points to the Earth's orbit determines whether and at what intensity meteor storms occur. If there is a storm, it occurs at the time when the Earth reaches the part of its own orbit that is nearest to the crossing point.

As an example, Fig. 3 is the situation in 1966, showing the places where trails cross through the ecliptic. Leonid orbits projected on to the ecliptic would be nearly parallel to the Earth's orbit in this region (with Leonid particles travelling in the opposite direction to the Earth), but the orbital planes of Leonids and Earth are inclined to each other by $\sim 18^\circ$. In Fig. 3, trail cross sections are idealised as ellipses, avoiding unnecessarily detailed discussion of the exact density profile. It is seen that the most spectacular meteor display of the 20th century occurred when the Earth passed near

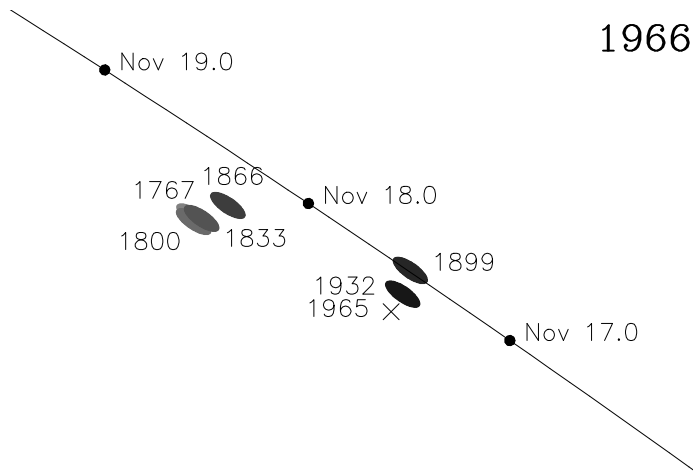


Figure 3. Cross sections of dust trails that passed through the ecliptic in 1966 November. Trails that were 1 to 6 revolutions old are plotted, labelled by the year in which they were generated (from 1932 back to 1767). The Earth's orbit is shown, and the Earth's position, exaggerating its physical size 10 times, at dates (Universal Time) in 1966. A cross indicates where the comet crossed the ecliptic in 1965, and does not represent a dust trail; although an incipient trail is present in 1965 (due to material being released at that perihelion passage), it does not extend far from the comet and is not present in 1966 November.

the centre of the 1899 trail, which was then 2 revolutions old.

The occurrence and timing of storms has been described as a 'predictable lottery'. It is a lottery in the sense that gravitational perturbations can shift dense dust trails away from the Earth's orbit, depriving the Earth of a meteor storm, or vice versa. But it is predictable because the perturbations can be accurately calculated.

2 RESONANT TRAILS

The 1998 outburst

The positions of young dust trails in 1998 are plotted in Fig. 4. No encounter of the Earth with a trail is evident. However, a second kind of trail is present in the Leonids (and other streams).

The dynamics of Leonid particles is ultimately chaotic, generally on timescales of a few centuries. Meteoroids that come close to the Earth during some perihelion passage (without actually impacting) are significantly deflected by the Earth's gravity. The gravitational effect can be enough to scatter them into the background Leonid stream, and so a (short) subsection of a trail that comes near the Earth is lost from the trail. Gradually, more of each trail is lost. A trail can survive as a narrow, coherent structure for a dozen revolutions or so, meaning that this number of 'normal' trails exist simultaneously, one for each of the comet's last dozen perihelion passages. Beyond this timescale, so much of a trail has been fragmented or scattered that it is no longer appropriate to regard it as a trail.

There is, however, a dynamical mechanism that can inhibit this chaotic scattering. Comet 55P/Tempel-Tuttle makes 5 revolutions of the Sun for every 14 of Jupiter.

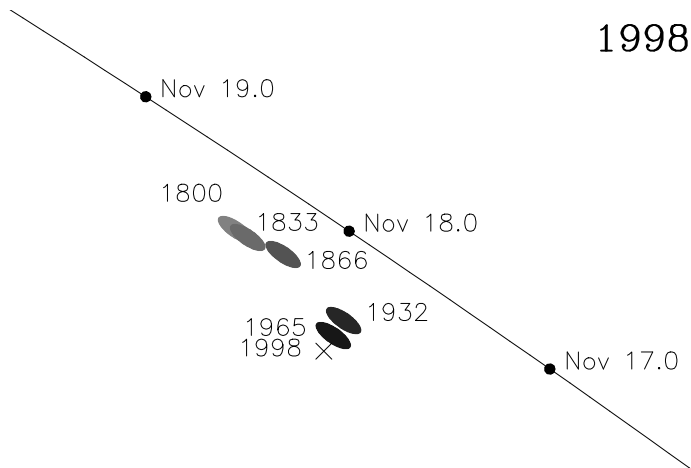


Figure 4. Cross sections of dust trails that passed through the ecliptic in 1998 November. The comet reached the point shown in 1998 March. The section of the 1899 trail that supposedly had the correct orbital period to bring it to the ecliptic in 1998 November had its evolution disrupted because of a fairly close approach to Earth in 1965.

The comet does not merely happen to have an orbital period that is in the region of $14/5$ times Jupiter's; instead it turns out that the gravity of Jupiter, the most massive perturbing planet, acts systematically on the comet, imposing this 5 to 14 pattern on the comet's orbital period. The comet is said to be in the 5 to 14 resonance with Jupiter. Although the comet's period may be slightly below the resonant value during one revolution, and slightly above during another, Jupiter keeps forcing the comet back to the 5 to 14 pattern in the average timing of the comet's returns. Such a resonant state can persist for many thousands of years, and the best estimate at present is that $55P$ /Tempel-Tuttle entered the $5:14$ resonance in the 7th century.

In the absence of resonances, particles in normal dust trails (Sec.1) would all be chaotically scattered into the Leonid background, with much of each trail having disappeared after a dozen revolutions. However, detailed dynamical studies [1], beyond demonstrating that $55P$ /Tempel-Tuttle and other orbits can be resonant, also reveal that (i) resonances can restrict particles to lie on quite narrow arcs over long timescales, rather than chaotic scattering into a wide region occurring; and (ii) the orbital evolution of particles in those arcs generally has a much higher degree of predictability, unlike with chaotic behaviour. Computer programs that evaluate planetary perturbations (cf. Sec.1) can therefore determine this evolution.

Any such arc of resonant particles develops from a small subsection, comparatively close to the comet, of one of the 'normal', younger trails. However, the resonant dynamics, over timescales of more than a few centuries, is qualitatively different from the dynamics controlling the normal trails. The resonant arcs therefore constitute a second kind of trail. But as with the normal trails, if the Earth runs through a resonant trail, a meteor outburst occurs. It was found [2] that a resonant trail consisting of a subset of the meteoroids released from $55P$ /Tempel-Tuttle in 1333 gave an excellent match to the peak time of the 1998 Leonid fireball outburst, with secondary components, including a resonant trail from 1433, contributing to the outburst's overall duration of many hours.

Resonances exist in the asteroid belt, in satellite systems and elsewhere in the solar

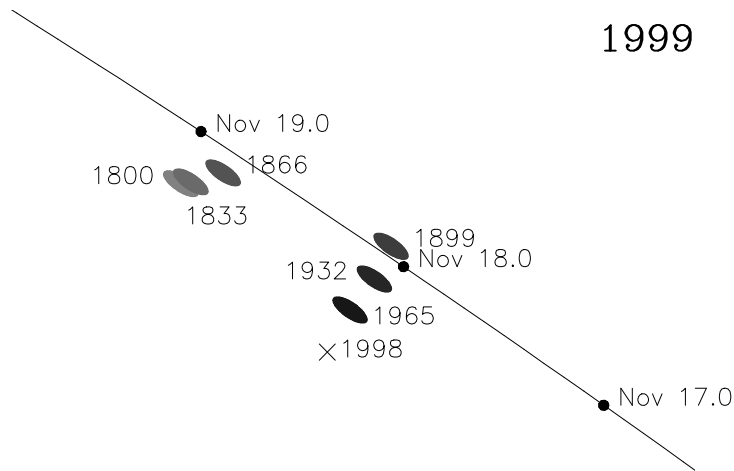


Figure 5. Cross sections of dust trails that passed through the ecliptic in 1999 November.

system. The 1998 Leonid fireball outburst was an observational demonstration that they exist in meteor streams.

Presence of fireball-producing particles

Because 55P/Tempel-Tuttle itself is resonant, and resonant orbits are defined by their orbital period, resonant particles are essentially those orbiting with periods most similar to the comet. In Figs 1 & 2, these are particles that do not quickly drift away from the comet's position, since it is the difference in period that causes particles to get behind or ahead. Comparison of Figs 1 & 2 shows that when radiation pressure is less (Fig. 1), i.e., for larger particles, the density peak is closer to the comet's position. In fact, it is generally expected that larger meteoroids are ejected at lower velocities from the comet nucleus; this effect would compress the concentration in Fig. 1 still closer to the comet.

Of course, smaller (usual visual meteor) particles are more numerous than larger (fireball) ones in total. The point is that smaller Leonid meteoroids have less tendency to occupy resonant regions, whereas a higher proportion of larger ones are inserted into resonant orbits similar to the comet's. So not only is the timing of the 1998 outburst predicted, but the preponderance of fireballs too.

3 METEOR STORMS 1999–2002

Comet 55P/Tempel-Tuttle, and the resonant zone containing the comet, have moved on in their orbit, not to return for another thirty years. Only the younger dust trails (Sec. 1) are relevant for the next few years. Figs 5–8 show the Earth encountering dust trails in 1999–2002. Various authors [3] independently found essentially the same times for some or all of the storms and outbursts resulting from these encounters. In Figs 5–8, trails as old as 9 revolutions are plotted (a limit of 6 revolutions was used in Figs 3, 4), and trail cross sections are absent from the plots only if there really is no ecliptic crossing at the relevant time in November (cf. absence of 1899 trail in 1998, discussed in Fig. 4 caption).

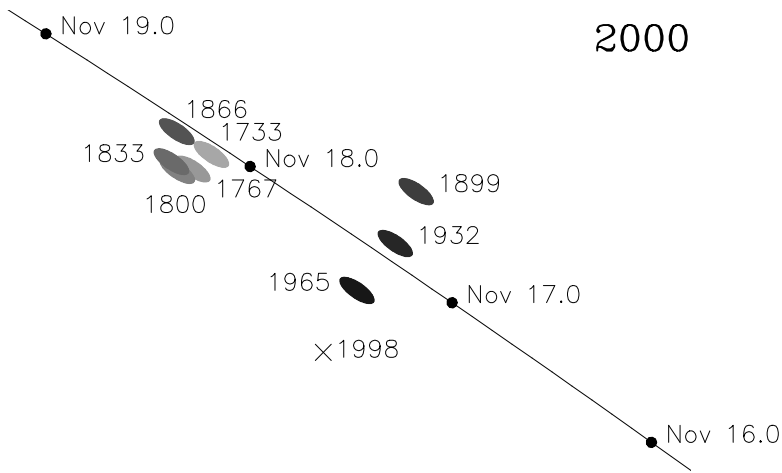


Figure 6. Cross sections of dust trails passing through the ecliptic in 2000 November.

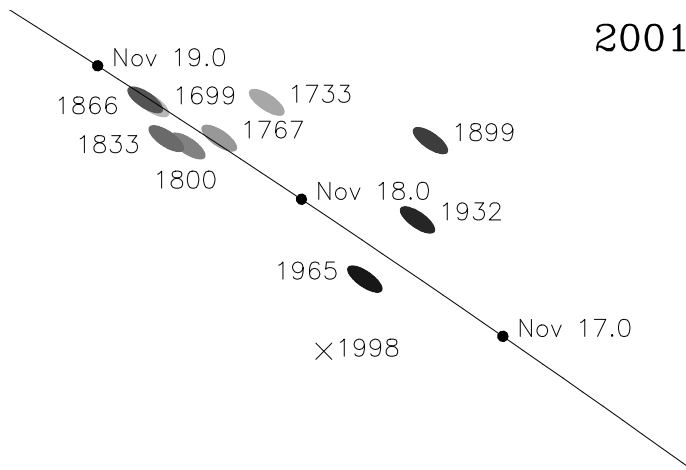


Figure 7. Cross sections of dust trails passing through the ecliptic in 2001 November.

A clear pattern is evident in Figs 4–8, where the cross section of any one trail has a tendency to be further, with each successive year, from the point where the comet crossed the ecliptic in 1998 March. That is, the various trails tend to become more separated in space, as one progresses further behind the comet, although some bunching (e.g., the cross sections shown for the 1800 and 1833 trails are quite close together) can occur. In terms of the probabilistic description of trail encounters, this corresponds to trail cross sections being randomly distributed over a wider region when one is further behind the comet, but as has been discussed, the random element is entirely removed by precise calculations of planetary perturbations.

The main purpose of this article has been to describe the structure within the Leonid stream, and to explain the dynamics of why trails are formed and how they evolve. The accuracy with which dust trail calculations can actually predict meteor storms in practice is discussed elsewhere [4]. A method to put the discussion of density profiles along and across trails (Sec. 1) on to a quantitative basis [5] implies that the highest ZHR

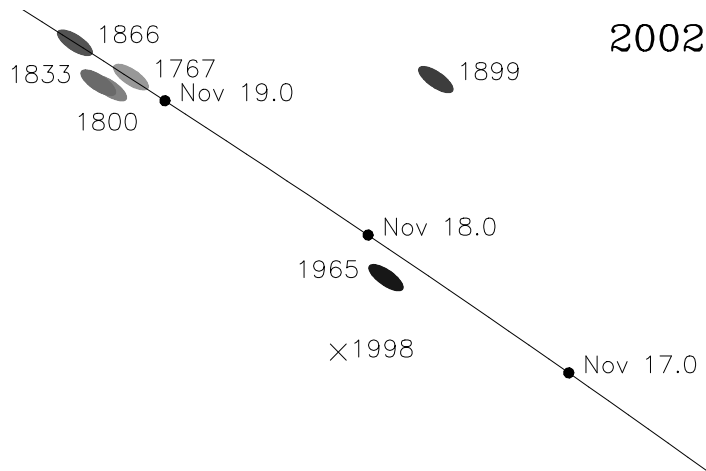


Figure 8. Cross sections of dust trails passing through the ecliptic in 2002 November.

Leonid storms of the present few years will occur in 2001 and 2002 (the former year having the advantage of new moon), when the Earth goes near the centres of various trails (Figs 7, 8). The increased distance from the centre of the 1899 trail in 1999 (Fig. 5) as compared to 1966 (Fig. 3) led to the ZHR being much less than in 1966. But as everyone at the 1999 Jordanian Leonid Meteors Conference knows, even the 1999 storm was quite something.

REFERENCES

- [1] For example, see V.V. Emel'yanenko & M.E. Bailey, 1996, in *ASP Conf. Ser. Vol. 104, Physics, Chemistry and Dynamics of Interplanetary Dust*, eds B.Å.S. Gustafson & M.S. Hanner, Astron. Soc. Pac., San Francisco, pp. 121–124, and other references given therein
- [2] D.J. Asher, M.E. Bailey & V.V. Emel'yanenko, *Mon. Not. R. Astron. Soc.*, **304**, L53–L56, 1999, and *Irish Astron. J.*, **26**, 91–93, 1999
- [3] E.D. Kondrat'eva & E.A. Reznikov, *Sol. Syst. Res.*, **19**, 96–101, 1985; E.D. Kondrat'eva, I.N. Murav'eva & E.A. Reznikov, *Sol. Syst. Res.*, **31**, 489–492, 1997; D.J. Asher, *Mon. Not. R. Astron. Soc.*, **307**, 919–924, 1999; R.H. McNaught & D.J. Asher, *WGN*, **27**, 85–102, 1999, updated on *IMO-News* (see <http://www.arm.ac.uk/leonid/last1999.html>); E. Lyttinen, *Meta Res. Bull.*, **8**, 33–40, 1999
- [4] R.H. McNaught, *The Astronomer*, **35**, 279–283, 1999
- [5] McNaught & Asher (*ibid.*)

Helpful comments from Robert H. McNaught led to significant improvements in the text. The article is based on my presentation at the 1999 Jordanian Leonid Meteors Conference. It is a pleasure to thank the Jordanian Astronomical Society for organising such a successful and enjoyable meeting.