The 2001 Leonids and Dust Trail Radiants

Robert H. McNaught and David J. Asher

On 2001 November 18th UT, the Earth will have close encounters with trails of meteoroids and dust generated over the past few centuries by Comet 55P/Tempel-Tuttle. It has previously been shown that these trail encounters will produce spectacular meteor displays, observers at east Asian longitudes and in North America having the chance to see this year's Leonid activity peaks in a moonless sky. Work by Lyytinen et al. has discussed the relevance of dispersive radiative effects in trail aging. In this article, we find that combining our existing ZHR model with an empirical aging parameter still leads to expected rates of several thousand from the east Asian trail encounters. We also consider what may be learned from high-resolution observations of radiants during such outbursts, of particular interest in 2001 because of meteor activity expected simultaneously from more than one trail. The Leonid radiant structure is shown to contain radiants from each dust trail separated by several arc minutes, and moreover each dust trail radiant contains its own internal structure which relates to the Comet's activity during the perihelion passage when the trail was generated.

1. Dust trail theories

Leonid meteor storms in November 2001 are now widely expected. These will occur when the Earth passes through dense, narrow trails of meteoroids and dust embedded in the Leonid stream. Several such trails exist, one being generated each time Comet 55P/Tempel-Tuttle returns to perihelion every 33 years or so, and typical lifetimes for trails' survival as narrow, coherent structures being of the order of a few centuries. The trails form and gradually lengthen because they consist of meteoroids having a range of orbital periods, particles of shorter and longer period progressively getting further ahead and behind, respectively.

As any one trail is much narrower than the whole Leonid stream, the Earth will usually miss most of the trails by a significant distance when it passes through the stream each November. However, trail positions are continuously shifted by gravitational perturbations and so it is necessary to evaluate these perturbations in order to see whether any trails are, in November of a given year, shifted to lie very close to the Earth's orbit. This would allow them to be encountered by the Earth, i.e., a high density of particles to impact the Earth's atmosphere and a meteor storm to be produced.

To determine trail positions with sufficient accuracy that all occurrences and non-occurrences of Leonid storms over the past two hundred years are correctly explained, it turns out to be sufficient to vary only one parameter. That is, ejection at perihelion is assumed and only the orbital period (at the time of ejection) is varied. For example, to determine whether meteoroids released from the Comet around its 1866 return (4 revolutions ago) come near the Earth in November 2001, particles ejected exactly at the instant of the 1866 perihelion passage are considered over a range of orbital periods and their evolution under gravitational perturbations (and, optionally, solar radiation pressure) through to November 2001 is calculated. An orbital period at the 1866 perihelion is determined that causes particles to reach their descending node in November 2001. If such particles cross the ecliptic at a heliocentric distance that is close to the Earth's orbit, then meteors will be produced. Moreover, the longitude at which they cross the ecliptic will correlate with the time at which the meteor outburst occurs. Calculations using essentially this technique have been performed by various groups and similar results have been derived (e.g., see [1–3]; the reader is also directed to these papers for references to earlier work).

Such calculations showed, for example, that the Earth encountered the 1733 (8 revolutions old) and 1866 (4-rev) trails in November 2000, but that the Earth missed the nominal centers of the trails by some distance. The peak ZHRs were therefore in the hundreds [4] rather than matching the levels reached in genuine meteor storms.

2. Leonids 2001 and ZHR fit including aging parameter

The dust trail technique predicts closer encounters of the Earth with Leonid dust trails in November 2001 than last year, leading to enhanced Leonid activity observable from North America and later from East-Asian longitudes on November 18 UT, 2001. The reliability of such predictions, firstly as regards the timings of peak activity, and secondly as regards the activity levels, is evidenced by the successful application of so-called dust trail models to all sharp Leonid outbursts in the past for which accurate observational data exist. We have previously mentioned that the idealized model (ejection from the Comet at perihelion in a fixed direction) might be imperfect for the encounter with the 7-rev trail (North America), because nearby points along that trail have been gravitationally disrupted during the intervening two centuries. Nevertheless, the chances are that the relevant part of the trail has survived as a dense, compact structure, so that the North-American outburst should occur.

The question of whether a higher ZHR will be observed during the earlier (North America) or later (East Asia) storm has received much attention. Results derived using a fuller model of ejection from the cometary nucleus [5] show enhanced meteor activity due to the same trail encounters found by the simpler idealized model. Reference [5] suggests the 6-rev and 5-rev encounters at intermediate times are also significant, leading to the activity profile being filled in over the intervening hours (between North America and East Asia). However, although some interaction with high velocity ejecta from 55P/Tempel-Tuttle 6 and 5 revolutions ago is likely, the moderately large miss distances calculated using the dust trail technique suggest no storm level activity from those encounters.

Table 1 – Parameters of Leonid trail encounters in November 2001 and 2002. Δa_0 specifies the point along the trail, given in terms of the semi-major axis difference from the Comet at the ejection epoch; the mean anomaly factor f_M is the inverse extent to which originally nearby particles have separated in the along trail dimension, at that point (negative f_M means mean anomaly is an increasing function of Δa_0); and $r_{\mathrm{E}} - r_{\mathrm{D}}$ is the distance in AU by which the Earth misses the nominal trail center (descending node of trail particles). This year, the Earth appears to encounter nearby but distinct points along the 7-rev trail. The ZHR fit is based on trail age, Δa_0, f_M and $r_{\mathrm{E}} - r_{\mathrm{D}}$, using data from 1866, 1867, 1869, 1966, 1999, 2000/4-rev, and two 2000/8-rev trail encounters close in time with assumed maximum ZHR of each equal to 135. A background ZHR of 30 is removed from all the 2000 dust trail ZHRs, the background becoming a significant contaminant of the dust trails with low ZHRs. The final decimal in these numbers is highly sensitive to the orbit adopted for the Comet.

Time (UT)	Trail age	Δa_0	f_M	$r_{\mathrm{E}} - r_{\mathrm{D}}$	Fitted ZHR
2001 Nov 18.382 ($09^{\mathrm{h}}10^{\mathrm{m}}$)	7-rev (a)	+0.096	−0.003	−0.00086	2
2001 Nov 18.413 ($09^{\mathrm{h}}55^{\mathrm{m}}$)	7-rev (b)	+0.085	0.156	−0.00048	800
2001 Nov 18.458 ($11^{\mathrm{h}}00^{\mathrm{m}}$)	7-rev (c)	+0.072	−0.005	−0.00010	70
2001 Nov 18.725 ($17^{\mathrm{h}}24^{\mathrm{m}}$)	9-rev	+0.046	0.401	+0.00010	2000
2001 Nov 18.733 ($17^{\mathrm{h}}36^{\mathrm{m}}$)	11-rev	+0.029	−0.022	+0.00020	40
2001 Nov 18.759 ($18^{\mathrm{h}}13^{\mathrm{m}}$)	4-rev	+0.146	0.139	+0.00018	8000
2001 Nov 18.780 ($18^{\mathrm{h}}43^{\mathrm{m}}$)	10-rev	+0.035	−0.011	+0.00004	40
2002 Nov 19.162 ($03^{\mathrm{h}}53^{\mathrm{m}}$)	7-rev	+0.117	0.132	−0.00013	3000
2002 Nov 19.437 ($10^{\mathrm{h}}29^{\mathrm{m}}$)	4-rev	+0.177	0.152	−0.00004	10000

For forthcoming encounters, we have derived a new fit of the peak ZHR to the miss distance $r_{\mathrm{E}} - r_{\mathrm{D}}$ and other parameters (Table 1). While the spatial density of particles varies in the across trail dimension, as parameterized by $r_{\mathrm{E}} - r_{\mathrm{D}}$, there is also a density variation in the along-trail dimension. We have previously used Δa_0 (Table 1) as the parameter for the latter, particles on smaller orbits having shorter periods and, therefore, moving towards the front of the trail (and vice versa). The along-trail density is expected to rise to a maximum, basically because the orbits of meteoroids will concentrate towards the orbit of the Comet, but the maximum in reality tends to shift behind the Comet, owing to solar radiation pressure. That shift is expected to be by an amount equivalent to Δa_0 of the order of +0.2 AU or so, for millimeter-sized particles (visual Leonids).

Thus, the particle density essentially depends on two spatial (along and across the trail) parameters Δa_0 and $r_{\mathrm{E}} - r_{\mathrm{D}}$. It also has a time (evolutionary) dependence. In our previous work, we only considered stretching of the dust trail as the aging effect. This was the f_M factor (Table 1) which is derived directly from calculation rather than having a density dependence fitted empirically. The cross-sectional profile of the trail is largely invariant under gravitational perturbations, and so this stretching is along the trail (to a simple approximation linear with age, but evaluation of gravitational perturbations allows an exact value to be found at a given point along a given trail). However, it is expected that additional non-gravitational factors will act to diffuse the dust trail cross-section [3]. An additional aging factor for the dispersion within the trail cross-section would have the density of an n-rev trail decreased by a factor y^{n-1} compared to a 1-rev trail, where y would be 1.0 if the cross-section were unchanging. Adding this parameter and including the *IMO* ZHR data for the 2000 4-rev and 8-rev trails gives $y = 1.38$. In fact, similar results are obtained excluding the 2000 4-rev and 8-rev encounters.

Attempting to include the 2-rev encounter from 2000 which occurred at the rather large distance $\Delta r = -0.0012$ reduces predicted ZHRs by a factor of about 3, but also spoils the fit to past data, particularly for 1966. Our model does not appear to extend to such values of $r_{\mathrm{E}} - r_{\mathrm{D}}$, and, especially for the close encounters of 2001 and 2002, it is more important to fit the storm region than the periphery. According to this fit, then, 38% of the ZHR is lost from revolution to revolution owing to diffusion in the cross-section. The ZHRs resulting from the fit done in this way, a topocentric correction having been applied to the past encounters, are listed in Table 1.

While working on this updated ZHR fit, we came across a few other points worth mentioning, from the calculations that determine trail encounter parameters ($r_{\mathrm{E}} - r_{\mathrm{D}}$, etc.). Multiple encounters, overlapping in time, with nearby but distinct points on the 8-rev trail occurred in 2000 (see also [3]); cf. 7-rev in 2001 in Table 1. Calculated times, not in Table 1 which only gives future encounters, are November 18, 2000, $3^{\mathrm{h}}23^{\mathrm{m}}$ and $3^{\mathrm{h}}33^{\mathrm{m}}$ UT, with a third encounter giving significantly lower rates about 20 minutes later. It is emphasized that these timings are dependent on the orbital solution for 55P/Tempel-Tuttle, which is the essential input to the calculations. In this paper, we use the orbit computed by Nakano in *Minor Planet Circular* 29285 from observations covering 1366–1997. The Comet's orbit over many centuries is known very accurately, but variations in cometary non-gravitational forces over this time scale allied with tiny astrometric uncertainties mean that the orbit can never be known to infinite precision. Therefore, while outburst timings can be predicted to an accuracy of several minutes, the times in Table 1 may differ from values we and others have published elsewhere.

For example, a different input orbit yields times 9–10 minutes later than the above for the 8-rev trail in 2000. A maximum recorded by video from an aircraft [6] with a peak at November 17, 2000, $7^{\mathrm{h}}48^{\mathrm{m}} \pm 4^{\mathrm{m}}$ UT is close to times we find for the somewhat distant 2-rev encounter, $7^{\mathrm{h}}45^{\mathrm{m}}$ and $7^{\mathrm{h}}51^{\mathrm{m}}$ UT for two Comet orbital solutions. The 4-rev trail was less well defined in the visual data from November 18, 2000, but appeared to arrive some tens of minutes earlier than the $7^{\mathrm{h}}41^{\mathrm{m}}$ or $7^{\mathrm{h}}51^{\mathrm{m}}$ UT that we now calculate. This may be due to systematic radiative effects [3], and also peaks may be less sharply defined when the Earth's passage through trails is away from their compact cores. The fit to the two stronger 8-rev encounters in 2000 indicates these had the same strength. The mid-time of these theoretical peaks is $3^{\mathrm{h}}28^{\mathrm{m}}$ UT, very close to the observer peak time of $3^{\mathrm{h}}24^{\mathrm{m}}$ UT [4]. This passage too was away from the core of the trail, but a tentative interpretation might be that the orbit utilizing the 1366 observations better represents the Comet's orbit for calculations involving old dust trails. The timing of young dust trail encounters is likely to be better than older ones for three reasons.

As noted below, dispersive effects may shift the peak time for older trails, and, with such broader activity, the peak also becomes more difficult to define from observation. Additionally, the younger dust trails involve ejection during the period for which the Comet's orbit is best defined, so that errors in the starting orbits of the ejected dust are smaller.

An additional factor affecting the ZHR fit is the position of the peak density in heliocentric radial distance, i.e., whether the maximum is displaced from the value of r_{D} calculated in the idealized model. We discussed that in our original paper, suspecting that the trail center might be displaced further from the Sun. Jenniskens [7] has argued that the trail center might be displaced closer to the Sun giving a peak at $\Delta r < 0$. However, this may be dependent on the assumption made by various authors (see below) that the profiles in the $r_{\mathrm{E}} - r_{\mathrm{D}}$ and ZHR dimensions are of the same form. Adjusting the value of r_0 (the dust trail center in heliocentric radial distance), in the fit that included the aging parameter, shows a pronounced minimum in the residuals around $r_0 = 0.0000$. Thus we find no evidence of any significant shift of the dust trail center. It should be noted that the relative strength of the 4-, 7- and 9-rev dust trails in 2001 is very sensitive to r_0, although even with r_0 shifted by -0.0004 AU, the North-American encounter never goes above a ZHR of 1000 in this model nor does it reach the highest East-Asian peak.

In all, various ZHR estimates for the peak activity due to the main trail encounters in 2001 have been published, e.g., [2,3,5,7] and Table 1 of this paper. These are calibrated using past Leonid data, and are referenced to dynamically realistic models (even if, e.g., the ZHR estimate does not come *directly* from a dynamical calculation of a dust trail position). There is, therefore, reason to regard them as reliable, although differences among the various estimates demonstrate the model dependence of the predictions. This model dependence can be contrasted with calculations of gravitational perturbations, the great success of Newtonian gravitational theory having been demonstrated for three hundred years. Leonid storm predictions neglecting planetary perturbations have about as much predictive power as astrology.

The results in Table 1 were calculated using gravitational perturbations *only*. Such results have been shown to apply to a high degree of accuracy for the sharpest Leonid outbursts of the past two hundred years. However, certain radiative forces might act systematically over a few centuries [3], causing a displacement in the time of peak meteor activity. This may be of the order of 20–30 minutes for the 7-rev and 9-rev encounters. These times are expected to be measurable observationally and should be among the many interesting results this November. Such differences in the modeling have little effect on what part of the world one decides to observe from, however. Similarly, while a moderate number of meteors from the 10-rev and 11-rev trails should be detected, anyone observing 9-rev and 4-rev meteors from East-Asian longitudes should experience the 10-rev and 11-rev encounters automatically.

We have considered a more general approach that would allow a fit of various ejection models to the observed peak ZHRs, outburst widths and mass distributions, but it was too involved to complete for the 2001 Leonids. Nevertheless, we note that in [3,5,7] it is assumed that the profile of a dust trail in heliocentric nodal distance ($r_{\mathrm{E}} - r_{\mathrm{D}}$) is of the same form as the ZHR profile, with different authors favoring a Lorentzian or a Gaussian. With this assumption, the width of the observed shower allows conclusions as to the location and density of the core for that dust trail encounter. However, we believe that a similar profile in these two dimensions is unlikely. The smaller the value of $r_{\mathrm{E}} - r_{\mathrm{D}}$, the greater the influence of particles ejected around perihelion, given that the node is placed very close to the comet's perihelion. For larger $r_{\mathrm{E}} - r_{\mathrm{D}}$, there may be no contribution whatsoever from particles ejected close to perihelion (see Section 3). Thus, the distribution of particles encountered at different $r_{\mathrm{E}} - r_{\mathrm{D}}$ will be a function of true anomaly and velocity of ejection, with the number of particles having the required velocity also being a function of the mass distribution of the ejected particles. For these reasons it is clear that more distant encounters will have a wider ZHR profile, even if no aging effect acts to diffuse the dust trails.

An attempt was made to make a generalized fit of activity width to several stream parameters, incorporating an aging effect. As noted above, the stream cross-sectional density decreases by a factor of $1/1.38 = 0.72$ per revolution. If this were due to an equal diffusion in both the heliocentric radial distance and the out of orbital plane dimensions, then, on each axis, one would expect diffusion to increase the width by $1.38^{0.5} = 1.17$. It is not clear what the ratio of spreading would be in these two axes, but determination of this ratio will have important implications for the nature of the dispersive effects. Despite an initial failure to make a generalized fit to stream width, there appear to be sufficient historical data, in the region of Δa_0, $r_{\mathrm{E}} - r_{\mathrm{D}}$ phase space where the major dust trail encounters of 2001 appear, to make an empirical determination of these stream widths. Thus, normalizing stream widths by 1.17^{n-1}, we derive an equivalent 1-rev ZHR FWHM of 32 minutes in 1966, 37 minutes in 1999, and 37 minutes in 1866. Then, interpolating from these and applying the width aging, we derive the following FWHM for the 2001 trails: 4-rev; about 70 minutes, 7-rev; 90 minutes, 9-rev; 130 minutes. The observed FWHM from the activity curve is dependent on the spreading out of the orbital plane. Should all the spreading occur in the heliocentric radial direction then the stream widths would be much closer to each other, based on the historical data, and all be of the order of 60 minutes. It is however most probable that stretching with age does occur out of the orbital plane and that the additional data from 2001 will help define the nature of the non-gravitational effects. It must also be stated that this model is very simplistic and ignores, for example, the likelihood of increased spreading of smaller masses. Another underlying assumption in all models considered by all authors is that splitting of particles after ejection is not a significant effect.

Given the limitations stated above, we still feel confident that our original double Gaussian fit with the addition of an aging factor gives an adequate representation of the storm region of dust trails. In 2001, we can expect a strong shower visible from North America and a guaranteed storm in East Asia.

3. The dust trail radiant signature

A consequence of the existence of multiple dust trails is that each trail will produce a slightly different radiant. The ejection velocities required for an Earth encounter at a specific time, and the subsequent orbital evolution of the particles, result in slight differences in direction and velocity at encounter. Conventional observing techniques may not be adequate to distinguish these differences, and the existence of "background" Leonids serves to further mask their existence. The velocity differences are small, of the order of 40 m/s in 2001, and no current observing technique could reliably distinguish such a difference. However, the difference between the mean radiant of one dust trail and another can be several arc minutes, a level quite adequate for longer focal length instruments.

The procedure to derive the dust trail radiant is similar to the original dust trail calculation referred to in Section 2 above as the "idealized model." This original calculation used ejection at perihelion (mean anomaly of zero) and an iterative process to find the required orbital period difference placing the dust at its node at the same instant the Earth lies at that nodal longitude. This defines a reference point on the dust trail from which subsequent calculations can be made. In the current calculations, we start at a variety of mean anomalies rather than just perihelion, and have as the end point a collision with the Earth's center at some specified time. This requires an iterative procedure including an additional factor, that of ejection direction, i.e., the procedure determines all three components of ejection velocity. Owing to non-linear behavior when integrating particles to the close proximity of a point-like Earth mass, integrations were terminated 0.1 days *before* a passage close to the Earth's center of mass, well within the Earth's radius, was indicated. Particles of interest were then integrated excluding the Earth's gravity, forward 0.098 days to a point closer to the Earth. The zenithal attraction caused by the Earth's gravity is considered separately (see Table 2, later) and is not accounted for in Figures 1–4.

The velocity vector representing the Leonid particle was then combined with the Earth's velocity vector (i.e., excluding diurnal aberration, which is also calculated separately and added to zenithal attraction to give the results in Table 2 later) at the collision time to give the geocentric radiant. Various tests including and excluding the gravity of the Earth-Moon system confirm that this procedure is valid. An assumption that we have not checked is that all particles that were ejected at a single mean anomaly and are on course to impact the Earth at a single instant

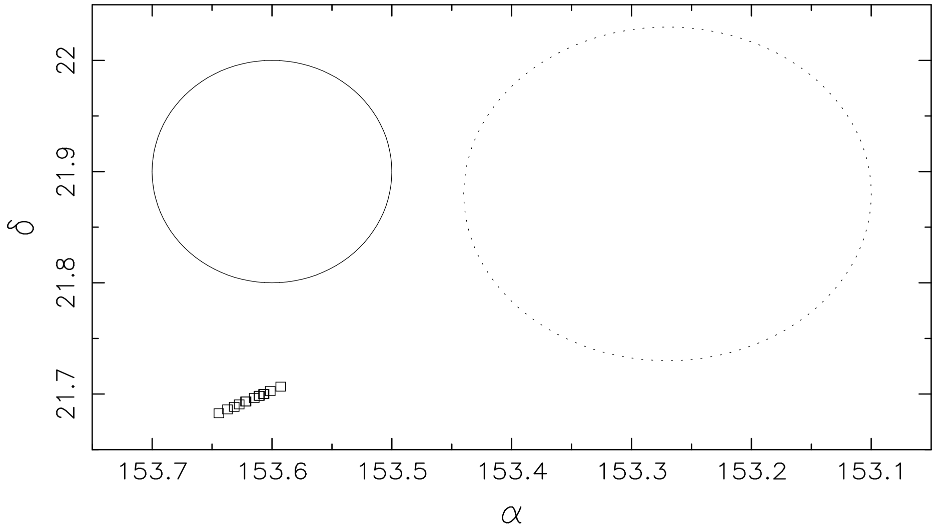

Figure 1 – Geocentric radiant structure of 3-rev trail (geocentric $v_{\rm g} \approx 70.65$ km/s; α, δ in J2000.0) at November 18.1 UT, 1999. Radiants determined observationally by Betlem (28 photographic double station meteors) and by Rendtel et al. (over 1100 video Leonids) [8], and their estimated uncertainty, are shown as dotted and solid outlines. Our calculation has been done at a solar longitude differing by about 0°.02 from that used in [8], but this is small compared to the observational uncertainty.

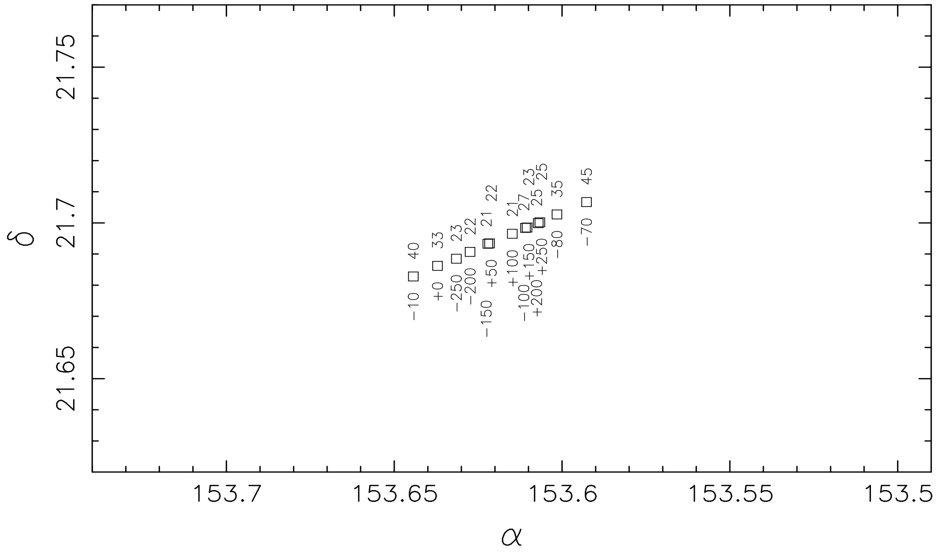

Figure 2 – Geocentric radiant structure of 3-rev trail at November 18.1 UT, 1999, i.e., as Figure 1, but enlarged so as to be on same scale as Figures 3 and 4. Each point is labeled firstly by the ejection time in days relative to the 1899 perihelion (±250 days corresponds to a heliocentric distance around 3.4 AU) and secondly by the magnitude in m/s of the unique 3-dimensional ejection velocity vector that allows a particle with radiation pressure parameter $\beta = 0.001$ to reach the desired Earth-impacting point at November 18.1 UT, 1999.

are moving on parallel paths as they approach, even if separated by approximately 10^4 km in space. This assumption is inherent in most considerations of radiants, and, even if it were to introduce a small error in the radiant position, the relative positions for the two dust trail encounters in 2001, and the internal radiant structure of these two dust trails, should be accurate.

The effect of solar radiation pressure on these results is insignificant, amounting to only about 0°.001 in the radiant position for a radiation pressure parameter $\beta = 0.001$ expected for visual Leonids. We have, therefore, not shown this in Figures 1–4. Any observed structure will result

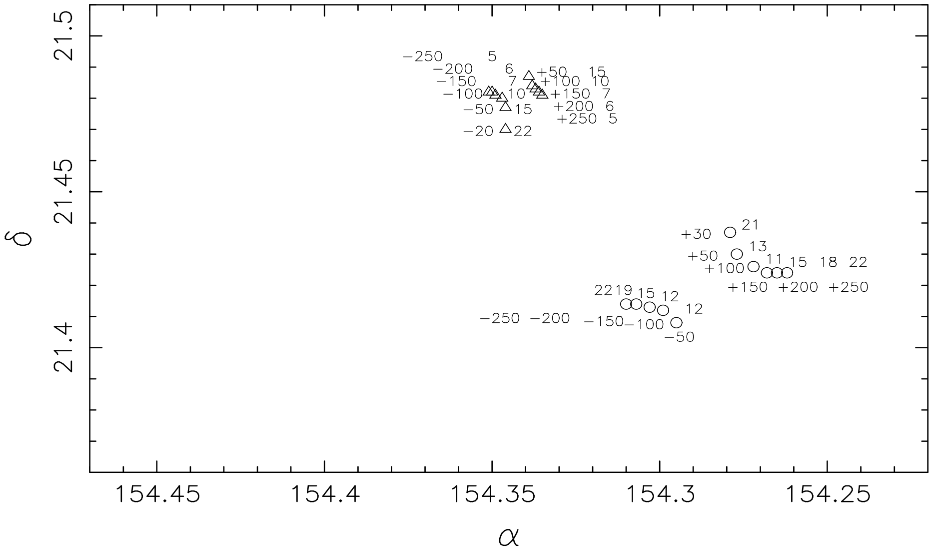

Figure 3 – Geocentric radiant structure of 4-rev (circles, $v_g \approx 70.69$ km/s) and 9-rev (triangles, $v_\infty \approx 70.65$ km/s) trails at November 18.7 UT, 2001. (Labeling explained in caption of Figure 2.)

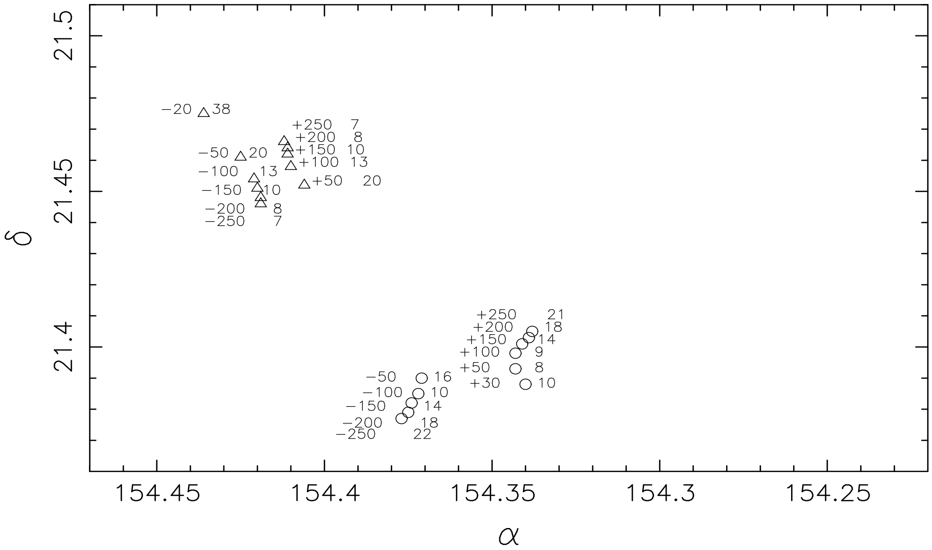

Figure 4 – Geocentric radiant structure of 4-rev (circles, $v_g \approx 70.69$ km/s) and 9-rev (triangles, $v_g \approx 70.65$ km/s) trails at November 18.8 UT, 2001. (Labeling explained in caption of Figure 2.)

from the ejection processes mentioned above, coupled with any other non-gravitational effects. The value of β does affect the tangential velocity that is required at ejection in order that the Earth impact is produced at the later date, although the other two components of ejection velocity are fairly insensitive to β. In Figures, 2–4 we have shown the magnitude of the ejection velocity in m/s, for β=0.001, as this is relevant if one is investigating ejection processes from the cometary nucleus. We have not listed the three ejection velocity components separately, but we mention that closer inspection of our results shows that for ejection within ±250 days of the 1899 perihelion passage, no impact solution in November 1999 exists with an ejection speed much below 20 m/s, for any reasonable (visual Leonid) β. That is, although β can be adjusted to reduce the required tangential ejection velocity, a significant component at right angles to this is needed. The 1999 storm therefore proves that ejection speeds above about 20 m/s exist, in a model where gravity and radiation pressure are the most important forces acting on meteoroids. Impact solutions in 2001 exist for very low ejection speeds, although, of course, the occurrence of the trail encounters this year will not preclude the existence of speeds above 20 m/s also.

Demonstrating the existence of dust trails through such a technique is hardly of consequence, as there is no doubt as to their reality. The aspects of importance are in the relative levels of activity from each dust trail radiant (as there will be overlapping activity in 2001), and in the internal structure of each radiant, something that could conceivably be used to investigate the activity of the cometary nucleus and ejection processes. Figures 3 and 4 give the radiant positions at two respective times during the 2001 encounters with the 4-rev and 9-rev trails. Other than the positional difference of the two dust trail radiants, there is evidently structure present within each trail. This structure results from the ejection of dust at different mean anomalies requiring different ejection speeds and directions to produce an Earth intersection at the specified future time. The resulting structure is of a curved line with each position representing a specific mean anomaly and ejection velocity from the specific cometary apparition. In both the 4-rev and 9-rev trails, there is a "zone of avoidance" towards the center of what can be called the dust trail radiant "signature." This region is a void if dust ejected from 55P/Tempel-Tuttle around its descending node, after consideration of subsequent orbital evolution, is sufficiently distant from the Earth's orbit that unrealistically large ejection velocities are required to produce the later Earth encounter. Therefore, no Leonids will be seen to come from that region. Thus, for each trail in Figures 3 and 4, the zone of avoidance splits the radiant structure into two parts that approximately correspond to ejection before and after perihelion, although this separation does not appear with the 3-rev trail in 1999 (Figures 1 and 2).

During the 1999 Leonid storm, a quasi-periodic variation in visual and video Leonid rates was detected [9,10]. A plausible mechanism for this was non-isotropic ejection from a rotating nucleus [9]. Reference [11] reported no evidence of these quasi-periodic variations from airborne video data. The probable explanation for this is that their video cameras were pointing low to the horizon and covering a substantial region of the meteor layer. This would require a correction of a few minutes between different meteors or small scale temporal variations could become hidden. Although the topocentric time correction is nominally defined as the observer's location, it should strictly be applied to the location of every meteor. In normal ground-based observation, this is mostly of little consequence, but, where the meteors are very distant from the observation location or they cover a large region of the meteor layer, a stricter use of the correction is required. A periodic variation might exist because particles ejected at different times (mean anomalies) show structure in the nodal longitudes, and so the Earth would pass through "waves" of particles at regular intervals. With only a single active area on the nucleus, this would be a very obvious effect, but multiple active areas would produce a quasi-periodic variability. As we have shown above that ejection at different mean anomalies produce a curved radiant signature, greater numbers of particles ejected at a specific mean anomaly should appear as a region of greater activity on the radiant signature. It may be possible to discern any quasi-periodic activity as a pattern of higher activity regions within the radiant signature. This could then be used to determine the rotation of the nucleus. The effect of particle ejection from active areas will vary between cometary apparitions and depend on the precessional state of the nucleus. Not every apparition need demonstrate this periodicity, but, as it appears to have been present in material ejected around the 1899 July perihelion passage, future encounters with the dust trail from this year should also show the effect. Diffusion with age will make this effect, when present, most marked in young dust trails, as diffusion will smear the peaks and troughs together.

Observers wishing to target the radiant exactly with narrow-field telescopes have to apply zenithal attraction and diurnal aberration to the geocentric velocity vector. This has been done for several locations listed in Table 2. As we have only recently developed our methodology for determining the geocentric radiant, we are not yet sure whether the small discrepancy between our calculations for 1999 and the observed position of the radiant in that year (Figure 1) indicates observational uncertainty or a systematic offset introduced by our methodology that should be applied to all our radiant calculations. However, the relative geometry of the radiant structure will be unaffected and the apparent positions in Table 2 represent the point on the 1866 dust trail at perihelion minus 50 days.

Table 2 – Apparent radiant corrected for zenithal attraction and diurnal aberration at various locations, at peak times of 9-rev and 4-rev trail encounters on November 18 UT, 2001. These values relate to the point in the 4-rev radiant signature resulting from ejection at perihelion minus 50 days. The same corrections would apply to other points in the radiant signatures.

Location	Time (UT)	α (J2000.0)	δ (J2000.0)	v_∞ km/s
Siding Spring	17^h13^m	$154^\circ.17$	$+21^\circ.12$	71.79
	18^h02^m	$154^\circ.34$	$+21^\circ.10$	71.75
Seoul	17^h24^m	$154^\circ.05$	$+21^\circ.72$	71.82
	18^h13^m	$154^\circ.21$	$+21^\circ.65$	71.79
Tokyo	17^h24^m	$154^\circ.18$	$+21^\circ.65$	71.80
	18^h13^m	$154^\circ.33$	$+21^\circ.60$	71.76
Xi'an	17^h25^m	$153^\circ.98$	$+21^\circ.73$	71.85
	18^h14^m	$154^\circ.01$	$+21^\circ.72$	71.84

The first time is the topocentrically corrected time for the predicted peak of the 9-rev trail and the second time for the peak of the 4-rev trail encounter on November 18, 2001. The geocentric position of this point in the radiant structure of the 4-rev trail at these times is $\alpha = 154^\circ.31$ and $\delta = +21^\circ.40$, respectively $\alpha = 154^\circ.33$ and $\delta = +21^\circ.39$. For other locations, the apparent radiant can be approximately interpolated from these positions. For time interpolations, the radiant motion can be approximately read off from a comparison of Figures 3 and 4, but for reference, the daily motions of the 4-rev and 9-rev trail radiants over the $\sim$0.1 day around the Earth's encounter with them are $\Delta\alpha = +0^\circ.71$ and $\Delta\delta = -0^\circ.27$ (this is approximately the average motion, for the various points in those two dust trail radiants).

Observations are planned from Siding Spring Observatory to look at the 2001 Leonid radiant structure using telescopes of several meters focal length, sufficient to be certain of deriving radiants with an accuracy significantly better than one arc minute.

References

[1] E.D. Kondrat'eva, I.N. Murav'eva, E.A. Reznikov, "The Leonid Meteor Swarm in 2000–2002", *Solar System Research* 34, 2000, pp. 237–240.

[2] D.J. Asher, R.H. McNaught, "Expectations for the 2000 Leonids", *WGN* 28, 2001, pp. 134–139.

[3] E. Lyytinen, M. Nissinen, T. Van Flandern, "Improved 2001 Leonid Storm Predictions from a Refined Model"", *WGN* 29, 2001, pp. 110–118.

[4] R. Arlt, M. Gyssens, "Bulletin 16 of the International Leonid Watch: Results of the 2000 Leonid Meteor Shower", *WGN* 28, 2000, pp. 195–208.

[5] P. Brown, B. Cooke, "Model Predictions for the 2001 Leonids and Implications for Earth-orbiting Satellites", *MNRAS* 326, 2001, pp. L19–L22; see also `http://see.msfc.nasa.gov/see/Leonid_Forecast_2001.html`.

[6] P. Jenniskens, B.Å.S. Gustafson, "The Rare 1932 Dust Trail Encounter of November 17, 2000, As Observed from Aircraft", *WGN* 28, 2000, pp. 209–211.

[7] P. Jenniskens, "Model of a One-Revolution Comet Dust Trail from Leonid Outburst Observations", *WGN* 29, 2001, pp. 165–175, see also `http://leonid.arc.nasa.gov/1998.html`.

[8] J. Rendtel, S. Molau, D. Koschny, S. Evans, O. Okamura, M. Nitschke, "Video Observations of the 1999 Leonid Meteor Storm Recorded at Different Locations", *WGN* 28, 2000, pp. 146–161.

[9] W. Singer, S. Molau, J. Rendtel, D.J. Asher, N.J. Mitchell, U. von Zahn, "The Leonid 1999 Meteor Storm: Verification of Rapid Activity Variations by Observations at Three Sites", *MNRAS* 318, 2000, pp. L25–L29.

[10] S. Molau, J. Rendtel, M. Nitschke, "First Results of Video Observations During the 1999 Leonid Storm", *WGN* 27, 1999, pp. 296–300.

[11] P. Jenniskens, C. Crawford, S. Butow, "Successful Hybrid Approach to Visual and Video Observations of the 1999 Leonid Storm", *WGN* 28, 2000, pp. 58–63.

Authors' addresses

Robert McNaught, P.O. Box 650, Coonabarabran, NSW 2357, Australia, e-mail `rmn@aaocbn.aao.gov.au`.

David Asher, Armagh Observatory, College Hill, Armagh, BT61 9DG, Northern Ireland,
e-mail `dja@star.arm.ac.uk`.