Expectations for the 2000 Leonids

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In the early hours (UT) of November 18, 2000, the Earth will encounter the 8-revolution old trail of meteoroids and dust from Comet 55P/Tempel-Tuttle, and, a few hours later, the 4-revolution trail. Neither encounter will be as close as in the cases that have given the greatest Leonid storms of the past. We discuss what is expected from the 2000 Leonid shower, and what one can hope to learn from it.

1. Introduction

Storms or sharp outbursts occur in the Leonids, and similarly in other meteor showers, when the Earth passes through a *dust trail*—a narrow structure where the spatial density of meteoroids is very high. A new trail is generated each time an active comet returns to perihelion. Trails soon become rather long; in the case of the Leonids, particles further forward in a trail can pass through the ecliptic some years before particles that are further behind in the same trail.

Leonid meteors can only be produced by particles that collide with the Earth. Since all meteoroids in the Leonid stream have their descending node in the region of the ecliptic moderately near where the Earth is in mid-November, in order for a meteor to be produced it is necessary that

- the meteoroid reaches its node in mid-November; and
- the node is very near to the Earth's orbit.

Leonid meteor storms can therefore be predicted by calculating the nodal positions of the parts of trails that pass through the ecliptic in mid-November [1–4].

For further explanation, results, and reviews of relevant work, see [3,5,6]. In the present article, we discuss some of the reasons why the dust trail technique has substantial predictive power, and make a few specific comments about how the theory applies to the 2000 Leonids.

2. Storm prediction using dust trail method

This method of storm prediction successfully explains storms *and* non-storms over the past 200 years. This absence of "false positives" *and* "false negatives" is strong evidence that the technique is applicable to Leonid storms. Since trails are much narrower than the whole Leonid stream, most trails pass too far from the Earth's orbit for a significant outburst to occur; however, outbursts have been observed when the "miss distance" is close enough. In Figure 1, the elliptical contours denote the combinations of parameters for which a peak ZHR of 1000 is expected, based on a model fit calculated in [3], with ZHRs tending to be higher towards the center of the ellipse. The ZHR evidently depends on the miss distance. It also depends on how long after the passage of the comet the trail encounter occurs. For plausible ejection processes from the cometary nucleus, it is to be expected that the highest densities of meteoroids will be on orbits most similar to the comet's orbit, immediately after ejection. However, solar radiation pressure on small particles causes the meteoroids to fall behind the comet by a progressively further amount on each revolution. Therefore, the potential for higher ZHR storms tends to be behind the comet, as also noted in [7].

There is a dramatic reduction in the size of the storm area (2 dimensional region of parameter space in Figure 1 plots) as compared with the situation [7] when the comet orbit, rather than trails, is used as the predictor; cf. last plot in Figure 1. This feature, even on its own, gives the dust trail method greater predictive power, but more conclusive still is the precision with which trail calculations estimate the peak time of outbursts [8,3].

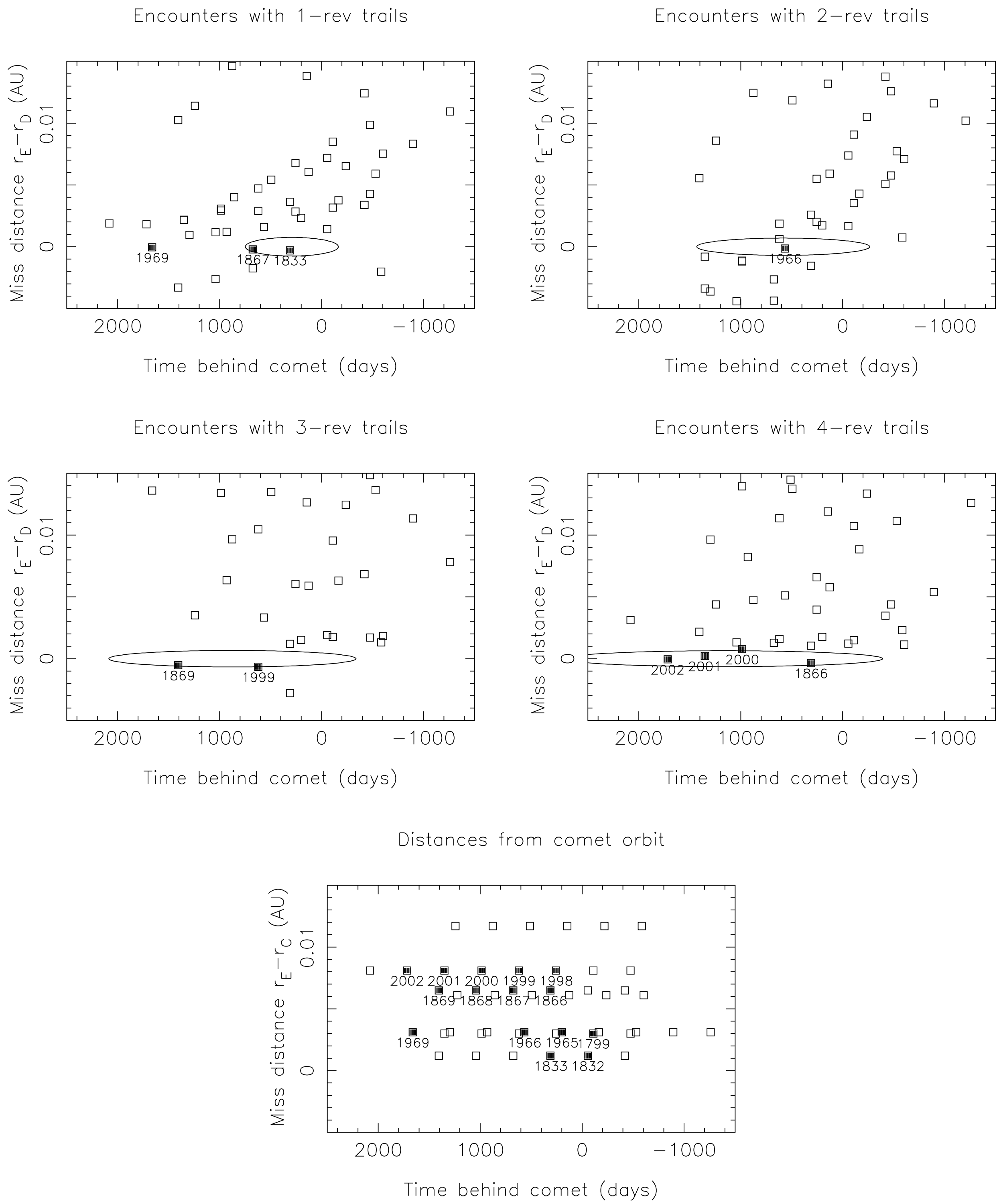

Figure 1 – Parameters of Earth encounters with Leonid dust trails, back to the 1800 return of 55P/Tempel-Tuttle. Data are given for 6 years at most returns, although there are one or two extra years around the two most recent returns (cf. [3], Table 1). Storms or sharp outbursts identified in Tables 2, 3, and 5 of [3] are shown as solid symbols, other years/encounters as open symbols. The miss distance from the nominal center of the trail is expressed as the difference between the heliocentric distances of the Earth and the descending node of particles in the trail, at the same longitude. The elliptical contour represents a model [3] fit of peak ZHR 1000, the peak ZHR for this particular model fit being assumed to reach a maximum when $r_{\rm E} - r_{\rm D} = 0$. The final plot relates to the node of the comet orbit rather than dust trail orbitss, some other years of enhanced displays being additionally shown as solid symbols; trails older than 4 revolutions caused 1799, 1832, and 1868 [2], with still older, resonant material causing 1965 and 1998.

Figure 1 makes it clear that for 1- to 4-revolution trails, there are no other encounters in the past 200 years where storms 4 years after the comet are expected (1969 was an outburst, but not a storm). There is, therefore, no inconsistency in the fact that storm level activity will occur in 2002 a greater time after the passage of the comet than on any other occasion in the past two centuries.

Our conclusions for the coming years are consistent with [1,4], very precisely as regards times of outbursts, and reasonably as regards levels of activity. However, they are not in agreement with some other predictions. Without attempting to be comprehensive, we shall comment on the reasons for discrepancies in some cases.

Rather low ZHRs have been predicted in [9] for the encounters with the 4-revolution trail in 2000–2002. In this paper, the authors correctly reject the fitting of a double function consisting of background and storm components in cases when the background component indicates a peak close in time to the storm component. It is more reasonable that these are activity from the same dust trail. True background activity would be more likely to peak hours, sometimes even days away from a specific storm peak, owing to the dramatically different evolutionary and perturbation histories. Thus, interpreting parameters of the dust trails from the 'storm component' alone of such a double function fit would give questionable results. Their use of a single Lorentz profile to fit the whole activity curve shows a clear improvement.

Given their success in fitting such a profile to the overall storm activity curve, they then assume that such a profile represents the radial profile of the dust trail. Although little data exist to define the radial profile, and, ideally, a theoretical approach based on the ejection of dust from the comet nucleus is needed, an empirical model could be of value. However, such a radial profile is used in [9] to fit to data on stream widths derived from observations in both storm and non-storm years. The major assumption here is that the non-storm year data are still representative of dust trails. It is easy to demonstrate that, in 1998 and 1965, the activity is unrelated to dust trails a few revolutions old, owing to the large time difference between the observed maximum and the predicted times of dust trails [10]. Thus, the data points on stream widths at large values of $r_\mathrm{E} - r_\mathrm{D}$ are unrelated to recent dust trails and cannot be fitted to the data at small values of $r_\mathrm{E} - r_\mathrm{D}$. The data at small values of $r_\mathrm{E} - r_\mathrm{D}$ alone are not sufficient to support the conjecture of a shift in the center of the dust trail.

Nevertheless, the main reason for the much lower rates (two orders of magnitude) in 2001–2002 in [9] compared to [1,3,4] appears to be the calculated decrease in density as mean anomaly increases, equivalently to density change as a function of time behind the comet, as shown in Figure 6 of [9]. However, there are crucial differences between their Figure 6 and our Figure 1 here, involving the use of scaled data from 10P/Tempel 2 as data points in constructing the curve of activity from 55P/Tempel-Tuttle and the Leonids, the plotting of data from trails of different ages against a single mean anomaly axis (whereas trails become longer as they age, hence the elongation of the ellipses with age in Figure 1), and the mean anomaly at which the ZHR peak is attained.

Our analysis [3] indicates that the peak ZHR of a 1-revolution trail occurs at $\Delta a_0 = +0.16$ (difference in semi-major axis of particles compared to comet, at time of ejection), which is consistent with theoretical predictions based on the effects of solar radiation pressure on visual meteoroids (cf. [1,11,12]) which yield a value of Δa_0 around +0.2. For a 1-revolution trail, this represents a mean anomaly of 9°–11°. Figure 6 of [9] is thus discrepant in having the ZHR peak for a 1-revolution trail at a mean anomaly of 0°. The 10P/Tempel 2 data appear to represent multiple undifferentiated dust trails, including 0-revolutions. This would be expected for an object with perihelion distance 1.48 AU (implying lower ejection velocities and thus slower separation from the comet) and period 5.5 years (implying trails have less time to dissipate in one revolution, and different revolution trails more strongly overlap.) Even if the 1-revolution dust trail of 10P/Tempel 2 could be dissociated from the other dust trails, it is unlikely that any meaningful ZHR could be derived from it that would be comparable with the observed Leonid

ZHR data used for the other points plotted. However, the most serious problem with Figure 6 of [9] is that the points for the trails in the years 2000 to 2002 use a mean anomaly of the 4-revolution trail plotted onto the function for a 1-revolution trail. Being 4-revolution, the mean anomaly for these three points should be divided by approximately four, which would place these three prediction points much higher up the curve, significantly increasing the ZHR. This is in addition to ZHR differences due to the width profile analysis, discussed in the previous paragraph. Other research giving very different estimates from [1,3,4] includes [13,14]. The method of [13] appears to be largely empirical, and discrepancies with other results are not surprising. The procedure followed in [14] is physically valid, being based on calculating the perturbations on meteoroids rather than on the comet, but the discrepancy is due to the spatial resolution applied. Essentially, there can be substantial variations in density even over very small distances, such as an Earth diameter (cf. Table 4 of [3]). Some discussion of other prediction methods appears in the CCNet archive [15].

3. ZHR model

Although the numerical parameters describing the model ZHR fit (i.e., the locations of the elliptical contours in Figure 1) were determined empirically from ZHRs of outbursts over the previous two centuries, the dependences on miss distance and time behind comet relate to existing physical mechanisms, namely ejection processes and radiation pressure. It is therefore reasonable to expect estimated ZHRs to be of the right order of magnitude. In [5], we estimated a peak ZHR, due to the 3-revolution trail in 1999, of 500, with the range 200–2000 being in accord with the model used and with observed ZHRs of the previous 200 years. The observed ZHR was 3700 [16]. Possible contributory factors to the discrepancy include the following:

- Although there is a physical basis for relating ZHR to miss distance and time behind comet, there is no theoretical basis for using a double Gaussian specifically.
- The 1833 maximum was derived in [17] from the available historical reports. However, this was some 45 minutes before our calculated peak time. Given the fits of later outbursts to within a few minutes, and given that the 1833 storm was not expected in the way that later ones were, it is reasonable to believe that the actual peak would have been some 45 minutes later and the peak ZHR considerably higher than the derived ZHR.
- Problems of visual counting in 1999 argue for greater ZHRs than derived in [17], for 1833 and 1966 in particular. Moreover, [17] explicitly states that many of the estimates of historical ZHRs are lower bounds.

Adjusting some of the past ZHRs (e.g., doubling the 1833 value and increasing 1966 to 110 000) allows a very good fit of 1999 to observations, within the context of the assumed double Gaussian model, although it must be noted that making such adjustments is rather subjective and cannot be done uniquely.

For reference, we list our latest estimates (Table 1), which we calculated including a topocentric correction to the distance in the $r_{\mathrm{E}} - r_{\mathrm{D}}$ term. These have been published previously in a review article [6]. Some visibility maps can be found in [18].

Table 1 – Trail encounters and outburst predictions.

Time (UT)	Trail	ZHR	Moon age	Visible from
2000, Nov 18, $03^{\mathrm{h}}44^{\mathrm{m}}$	8-rev	100?	22	W. Africa, W. Europe, NE S. America
2000, Nov 18, $07^{\mathrm{h}}51^{\mathrm{m}}$	4-rev	100?	22	N. America, C. America, NW S. America
2001, Nov 18, $10^{\mathrm{h}}01^{\mathrm{m}}$	7-rev	2500?	3	N. and C. America
2001, Nov 18, $17^{\mathrm{h}}31^{\mathrm{m}}$	9-rev	9000	3	Australia, E. Asia
2001, Nov 18, $18^{\mathrm{h}}19^{\mathrm{m}}$	4-rev	15000	3	W. Australia, E., S.E., and C. Asia
2002, Nov 19, $04^{\mathrm{h}}00^{\mathrm{m}}$	7-rev	15000	15	W. Africa, W. Europe, N. Canada, NE S. America
2002, Nov 19, $10^{\mathrm{h}}36^{\mathrm{m}}$	4-rev	30000	15	N. America
2006, Nov 19, $04^{\mathrm{h}}45^{\mathrm{m}}$	2-rev	100	28	W. Europe, W. Africa

4. Leonids 2000

The Earth will encounter the 8-revolution and 4-revolution trails at the times given in Table 1, with western Europe and western Africa being favored for the former, and North and part of South America for the latter. Outbursts will occur, our best estimate being that they will occur at well below storm level. Other authors who have made calculations relating to these trail encounters [1,4] estimate rather stronger activity (at the same times, which are very accurately known), which we regard as quite possible. The main reason for the uncertainty in the activity level is the lack of encounters, over the previous two centuries, having similar parameters: in particular, it simply happens to be the case that all the main data points have $r_E - r_D < 0$, opposite to the situation in both cases in 2000. The best constraint on 2000 may be 1801 (this is the unlabeled point just above 1966 in the 2-revolution plot of Figure 1). We are not aware of a meteor outburst or storm having been observed and recorded at that time, as discussed further in [3]. Clearly, activity up to some level could have been missed, or not recorded, but it is hard to say exactly what this level is.

The 4-revolution encounter in 2000 should prove that the 4-revolution trail, to be encountered again, further back along its length, in 2001 and 2002, does indeed exist, although, really, this is known in any case, since the comet was active enough (and so releasing meteoroids) to be discovered in 1865–66. Other authors [1,4] and ourselves agree as to the virtual certainty of higher (storm level) ZHRs in 2001 and 2002. The fact that the miss distances are significantly smaller in the 2001–2002 encounters may limit the influence 2000 will have on the predictions for the next two years. Perhaps of greatest interest this year, will be the relative strengths of the two trail encounters, although, with the 8-revolution trail, the interpretation may be made more uncertain because of the proximity of the encountered section of the trail to parts of the trail that have been disrupted.

The 8-revolution and 4-revolution encounters occur the night after the Earth's passage through the plane of the Comet's orbit. Of course, observers are strongly recommended to observe on more than one night, for other possible Leonid activity. For example, the night before the 4-revolution encounter, a shower of small meteors from the 2-revolution trail should be visible [4] from America, albeit the miss distance is less favorable than for the 4-revolution encounter. The extent to which distant encounters with trails have produced activity in the last two years is not completely clear, but is likely to be quite small, since the time of activity should be within a few minutes of prediction. The accuracy with which observed times match nominal calculated times of encounters with trails was shown [10] to be the first observational evidence that dust trails are substantially flattened sheets.

Present knowledge of background activity from the Leonids is less detailed than that relating to particular trail encounters. We have checked the evolution, under gravitational perturbations, of material ejected at every perihelion return of 55P/Tempel-Tuttle over the past 1400 years, by integrating particles separated by 0.01 AU from 0.2 AU below to 0.6 AU above the cometary value at the time of ejection. No obvious initial orbits that resulted in intersection with the Earth in 2000 were found, other than the solutions already known. It is conceivable that the resolution of 0.01 AU was insufficient, causing solutions to be missed (although a few particles were integrated at a finer resolution around what appeared to be the most promising cases). The chances are that the 8-revolution and 4-revolution encounters will produce the highest activity overall during the 2000 Leonids.

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