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The 1999 Leonid meteor storm: verification of rapid activity variations by observations at three sites

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ABSTRACT

We report observations of an unpredicted fine structure in the activity profile of the Leonid meteor storm of 1999 November 18. Our observations were obtained at three widely separated sites (on the Iberian peninsula, in Germany, and in northern Sweden) and with two totally different techniques (video cameras and meteor radars). The observations clearly show quasi-periodic variations of the meteor rate with temporal separations of individual maxima in the 6- to 9-min range. These temporal variations translate into spatial variations within the dust trail with scales between 10 000 and 30 000 km, depending in which reference frame or direction one chooses to compare. The times for the central three maxima as observed at the three sites agree within 2 min of each other after application of the appropriate topocentric time corrections. We consider a number of potential causes for the observed density variations within the meteor stream.

Key words: comets: individual: Tempel–Tuttle – meteors, meteoroids.

1 INTRODUCTION

The processes of formation and evolution of meteoroid streams have long met with great interest in the scientific community, by both amateurs and professionals. Those meteoroid streams that exhibit high dust flux rates produce at times meteor storms, spectacular displays of frequent meteors in the night sky. For various reasons, however, it is difficult to predict the exact time of encounter of such meteoroid streams with the Earth, as recently exemplified by the 1998 Leonids. Their impressive fireball activity occurred in fact about 24 h before the time when the genuine Leonid storm was predicted by most astronomers.

This scenario changed to a more predictable one with the 1999 Leonid storm. Asher (1999) described how high-density trails in the Leonid stream, each formed during one of the more recent perihelion passages of Comet 55P/Tempel–Tuttle, could remain narrow for at least a few revolutions. Before the meteoroids in a trail become scattered over a wider region, the trail maintains the potential to produce a storm, which occurs if the Earth passes through the trail. Using essentially the same technique of evaluating gravitational perturbations at points along trails, Kondrat'eva & Reznikov (1985), McNaught & Asher (1999a) and Lyytinen (1999) predicted that the peak activity of the 1999 Leonid shower would occur on the morning of 1999 November 18, their estimates being from 02:08 to 02:10 UT. At this time the Earth would be at the centre of its encounter with the trail caused by dust ejected from the comet during its 1899 perihelion passage. McNaught & Asher (1999a,b) compared calculated times with storm and outburst peaks of the past two centuries that had been accurately observed, showing that the uncertainty in the calculations could probably be reduced to 5 min. Within an hour after the predicted time it became obvious from many ground-based observations (see e.g. Gyssens 1999) that the maximum had occurred within the error bar of the prediction. This was quite a contrast to the situation one year earlier!

With this report we want to carry one full step further the studies of the fine structure of the Leonid meteoroid stream. So far, we have discussed the existence of dense dust trails as a 'fine structure' of the general Leonid meteoroid stream. Crossings of the Earth through these dust trails occur on time-scales of an hour. In the following, we will present for the first time evidence for the fact that even within the dust trails there exists a significant small-scale fine structure. Crossings of the Earth through these sub-trails occur on time-scales of less than 10 min. For an identification of such short temporal variations in the Leonid stream, one needs to collect observations on a no longer than 1-min basis. The peak visual zenithal hourly rate (ZHR) of the 1999 Leonids came close to 3700 (Arlt et al. 1999). Yet, for good reasons, many visual

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Table 1. The main properties of the video cameras.

Camera	Operator	Country	Location		Time[a]	Obs.[a]	FOV[a]	LimMag[a]		#Leo[a]
			Long.	Lat.	UT	time	(°)	Sta.	Met.	
AVIS	Molau	Spain	4°.33W	36°.95N	0002–0405	4:03	15	9.0	(7.0)	212
CARMEN	Rendtel	Spain	4°.33W	36°.95N	0004–0405	4:01	28	5.5	(4.5)	459
EMILY	Evans	Portugal	7°.22W	37°.18N	2309–0614	7:02	40	5.5	(4.5)	543
ELLI	Elliot	Portugal	8°.60W	37°.15N	2315–0615	6:59	50	5.5	(4.5)	678
Mean or Total			5°W	37°N		22:05				2964

[a] Time UT = analysed interval; Obs. time = net recording time; FOV (°) = diameter of the field of view; LimMag Sta. = limiting magnitude for stars; LimMag Met. = limiting magnitude for meteors; Leo = number of recorded Leonids.

observers and automatic recording devices (cameras, radars, etc.) out in the field have observed considerably fewer meteors. Their rate of observed meteors was, say, 25 per minute near the activity maximum and correspondingly less at the flanks of the maximum. It is clear that, with an event rate of less than 25 per minute, a statistically significant result concerning variations with time-scales of the order of 10 min (and less) is difficult to come by with a single recording device. In order to enhance the significance of our result with respect to an observed fine structure, we have chosen to combine data sets from three different sites which were separated by thousands of kilometres from each other. In addition, we combine data obtained by video cameras with those of meteor radars. After presenting our observational results, we discuss candidate processes that might be causing the sub-trail fine structure.

2 OBSERVATION SITES AND TECHNIQUES

For our observations of the 1999 Leonid meteors, we have used the following sites and techniques: site 1a near Malaga, Spain, equipped with two video cameras; sites 1b and 1c in southern Portugal, each equipped with one video camera; site 2 at Juliusruh, Germany, equipped with a meteor radar; and site 3 at Kiruna, Sweden, equipped also with a meteor radar. Because sites 1a, 1b and 1c are close to each other in comparison with their separation from sites 2 and 3, we will in the following consider them jointly as site 1 ('Iberia'). The distance from the Iberian site to Juliusruh is about 2300 km; that between Juliusruh and Kiruna is 1600 km.

2.1 Site 1 (Iberia)

Our video observations of the 1999 Leonids were obtained with the help of four intensified video meteor cameras located in southern Spain and in Portugal. They were operated by amateurs from the Arbeitskreis Meteore (Germany) and the British Astronomical Association (UK). The main parameters of the sites and cameras can be found in Table 1. All cameras were unguided, so that the atmospheric volume under examination remained constant during the storm. The data obtained by the four cameras were added to one larger data set. This allowed the determination of better activity profiles than those presented in the first analysis right after the storm (Molau, Rendtel & Nitschke 1999).

All data were recorded on VHS video tapes and subsequently analysed in two steps. First, meteors were automatically detected using the METREC software package (Molau 1998). Then, the near-peak period was also visually inspected to ensure maximum meteor detection probability. Meteors that did not belong to the Leonid stream according to their direction or angular velocity were excluded from further analysis. The AVIS and CARMEN cameras had the same field centre, but a different limiting magnitude. Identical meteors were counted only once in the following calculations. The Leonid rates derived from individual cameras show strong temporal variations. However, cameras at nearby locations like the four chosen for this analysis clearly showed similar patterns, allowing us to add the counts and obtain a more significant mean profile for the southern part of the Iberian peninsula (see Section 3).

2.2 Site 2 (Germany)

The meteor radar of the Leibniz-Institut für Atmosphärenphysik is located at Juliusruh on the island of Rügen, Germany (54°38′N, 13°24′E). It is a commercially produced all-sky interferometric meteor radar ('SkiYMet') operating at a frequency of 32.55 MHz and a peak envelope power of 12 kW. We note that the system detects only meteor trails oriented perpendicularly to the radial direction from the radar to the meteor trail. The radar uses a five-antenna interferometer with circular polarized antennas on transmission and reception (Hocking, Fuller & Vandepeer 2000). A range accuracy of 2 km and angular accuracy of 1° to 2° in meteor location were possible. In the Leonids experiment the objective was to locate as many meteors as possible, as well as to determine entrance velocities. A two-point coherent integration was used in order to optimize the time resolution for entrance speed estimation, resulting in a sample resolution of 0.94 ms at a pulse repetition frequency of 2144 Hz. The radar was configured for a cut-off altitude of 120 km and was operated in this mode from November 15, 21:00 UT until November 20, 14:00 UT. From the raw data we removed double and multiple detections of single trails by comparing all trails within any 3-s time-slot for their detection time, range and azimuth. Thus some echoes with ambiguity level different from 1 have been included in our statistics (obviously only once). During the critical storm period between 02:00 and 02:20 UT, they contribute 27 per cent to the total radar meteor rate.

2.3 Site 3 (Sweden)

The University of Wales Aberystwyth radar is located at Esrange (67°53′N, 21°06′E) near Kiruna in northern Sweden. This radar too is a SkiYMet system. It operates, however, with a peak power of 6 kW. The radar uses crossed antenna elements to ensure a near-uniform azimuthal sensitivity to meteor echoes. During the time of the Leonid shower the radar was operating in a mode optimized for meteor drift measurements of mesospheric winds, and so it did not reliably record meteors at heights greater than 110 km. The procedure for removal of double and multiple detections of single

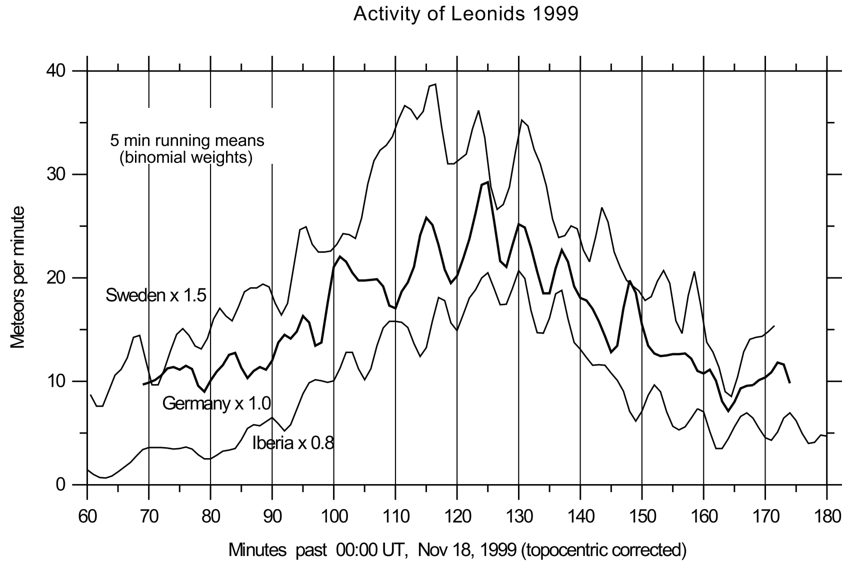

Figure 1. Meteor rates (min^{-1}) versus UT time (topocentric corrected) at our sites in Iberia, Germany and Sweden.

trails from the raw data was the same as applied for the data of site 2.

3 THE OBSERVATIONS

3.1 Data processing and results

During the period 01:00 to 03:00 UT on 1999 November 18 and for each of the three sites, the number of meteors was counted for each full minute. Then we calculated 5-min running means (with weights 1–4–6–4–1) of the meteor rates (min^{-1}) and applied the topocentric time correction to the time axes of the three curves. The latter correction accounts for the fact that calculations of the time of Leonid maxima are commonly based on the centre of the Earth and must be adjusted to give the observed time of maxima from any specific location (McNaught & Asher 1999b). The corrections are −1, −3.5 and −6 min for our sites 1, 2 and 3, respectively. In Fig. 1 we show the result of this data processing: the meteor rate (min^{-1}) versus UT time (topocentric corrected) as measured at our three sites. It turns out that, for all three sites, the absolute rates of observed meteors are rather similar and about 25 min^{-1} during the peak of the Leonid activity. To make the individual curves better traceable in Fig. 1, we have multiplied the rates observed in Sweden and Iberia with factors of 1.5 and 0.8, respectively.

We remind the reader that the meteor rates given here apply for the sum of the rates of four cameras. As shown in Table 1, their fields of view and limiting magnitudes are not identical. Nevertheless, we can estimate the sensitivity of the radars by comparing their meteor rates with that of one of the cameras. For this comparison, we choose the AVIS camera as it is the most sensitive of the four cameras. Its peak meteor rate during the Leonid storm reached 8 per minute, whereas the radar rates peaked near 25 per minute. We estimate the sensitive collection area of the radars to be twice as large as that of AVIS. This indicates that the limiting magnitude of the radars is perhaps 0.5 mag larger than that of AVIS, or approximately 7.5. This value should be considered a first approximation of the radar limiting magnitude only, not a genuine calibration.

The observations from all three sites (Fig. 1) indicate the existence of a considerable fine structure in the dust trail that produced the 1999 Leonid storm. The variations have time-scales of less than 10 min and are thus shorter than any earlier observations of this kind. In our observations, the statistical error bars of individual points are 12 per cent near the activity peak. This statistical uncertainty is certainly less than the observed 'depth of modulation' of the curves. We argue, though, that the most important evidence for the existence of the multiple maxima comes not from single-station observations, but rather from the fact that coincident maxima are seen at three (!) widely separated sites and by using two (!) totally different and automatic observation methods.

Near the beginning and end of the observation period of Fig. 1, the meteor rates are rather small. Hence the fine structure shown during these periods in the three individual curves is of much reduced significance.

We note that the depth of modulation (ratio of neighbouring minima over maxima) as exhibited in the three curves of Fig. 1 depends somewhat on the smoothing procedure applied to the curves. Furthermore, the two sets of radar data contain *all* meteors (sporadic, shower and storm meteors), not only Leonids. For the radars, the meteor rates during the peak of the storm were approximately 25 min^{-1}, of which about 5 were produced by sporadics and shower meteors (as derived during the nights before and after the storm). Assuming that sporadic and shower meteors do *not* contribute to the short-time-scale modulations, their subtraction from our data would further increase the modulation depth in the variations of the genuine storm Leonids.

3.2 Quantitative analysis of the observed fine structure

Most notable in the observed fine structure are the three maxima at about 01:55, 02:03 and 02:10 UT, all of which were well observed at each of our three sites. In order to quantify better a possible wave period in our data, we performed for each of our complete data sets a wavelet analysis of the meteor rate fluctuations in the data (after having subtracted from the data a smoothed mean function). Fig. 2 shows the result of the wavelet

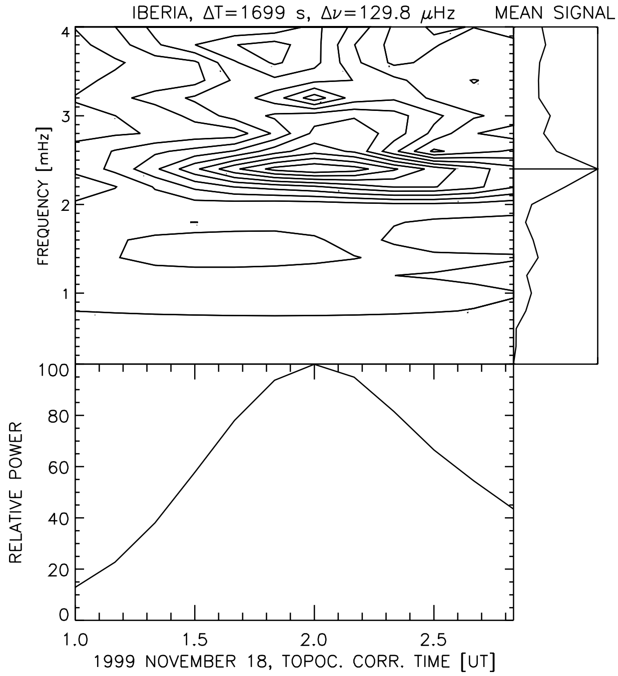

Figure 2. Wavelet analysis of the meteor rate fluctuations observed on the Iberian peninsula. The upper left panel shows the isolines of oscillatory power during the period analysed (maximum set to 100). The upper right panel gives the sum of power over the frequency range with the most prominent frequency marked by the dot–dashed line. In the lower panel the temporal behaviour of the relative power of the most prominent fluctuation is plotted. ΔT and $\Delta\nu$ are the time resolution and the frequency resolution, respectively.

Table 2. The most prominent frequencies (and periods) of activity variations of the 1999 Leonid storm.

Iberia	2.4 mHz	(6.9 min)
Germany	2.0 mHz	(8.3 min)
Sweden	2.4 mHz	(6.9 min)

analysis for the data from the Iberian site. The upper left panel shows the isolines of oscillatory power during the analysed period (maximum set to 100). The upper right panel gives the sum of power over the frequency range, with the most prominent frequency marked by the dot–dashed line. In the lower panel the temporal behaviour of the relative power of the most prominent fluctuation is plotted. We find the highest power close to 02 UT. ΔT and $\Delta\nu$ are the time resolution and the frequency resolution, respectively. Identical wavelet analyses have been performed for the data from the German and Swedish sites. Table 2 gives the most prominent frequencies and periods founds for the data at each of the three sites. The similarity of the periods, derived independently for the three sites, is very encouraging. Their mean is 7.4 min.

As a byproduct of the wavelet analysis, we obtain from the smoothed curves the times for the activity peaks (all topocentric corrected) as 02:03.0, 02:08.0 and 02:02.5 UT for Iberia, Germany and Sweden, respectively. As an average of the three times quoted above we obtain 02:04.5 UT (±3 min) which is indeed within 4 min of the time of 02:08 UT predicted by McNaught & Asher (1999a).

3.3 Comparison with other observations and literature

This paper is not meant to provide a systematic survey of the very numerous visual observations of the 1999 Leonid storm. A very useful introduction to this material has been given by Arlt et al. (1999). Only six weeks after the 1999 Leonid storm, these authors cited 434 observers who reported on 277 172 visually observed Leonids. Arlt et al. (1999) used binning intervals of 2.8-min length for their analysis. Here we wish to cite three particular observations from the Arlt et al. bulletin. (i) The authors derive from the more than 200 000 visually observed Leonids a time of peak activity of 02:02 UT (±2 min). (ii) Their ZHR profile exhibits a few short-term enhancements at e.g. 01:25, 01:43, 01:50 and 02:33 UT. (iii) If the total data set is split into three (centred in the Near East, southern France and southern Spain), each of which still contains more than 10 000 Leonids, the short-term enhancements in the three data sets barely agree in their timing and depth of modulation. We compare these three observations with ours as follows. (1) Our time of maximum activity, derived from automatic recording devices, agrees well within the combined error bars with that derived from the visual observations. (2) The depth of modulation in the fine structure is considerably smaller in the visual observations than that in our observations. A potential cause of this difference may be a difficulty of visually recording meteor rates of the order of 1 per second with good accuracy. (3) We point out the fair agreement of observed fine structure at three widely separated sites. Why the same scenario does not yet prevail for the visual observations as well is not fully understood.

Arlt et al. (1999) have attempted to reproduce the observed activity profile, using the same modelling procedure as used by Arlt & Brown (1999). Their fig. 7 shows the modelled ZHR with some superimposed fine structure. However, the period of this structure turns out to be 17 min and is thus 2.3 times longer than observed. Hence the cause of fine structure in the dust trail(s) of the Leonid stream remains to be discussed.

4 INTERPRETATION

As the observational evidence is strong that the secondary peaks, occurring on time-scales of about 7 min, are real, the question arises as to how such structure could be present. The times of these sub-peaks, which are evident only during the 1899 trail encounter, suggest that they are associated with that trail. The only other trail calculated to be (moderately) close is the 1932 trail, with a predicted peak time of 01:44 UT.

The time variations in the meteor rate reflect spatial variations in the meteoroid density along the Earth's path through the trail/stream. For example, 7 min represents 13 000 km (measured in the ecliptic, not a perpendicular cross-section through the stream). Numerical integrations show that structures on scales of a few times 10^4 km, or indeed less, can survive between 1899 and 1999 (e.g. see fig. 1 of McNaught & Asher 1999a). The question is therefore how the structure could be created in 1899. A smoothly varying meteoroid production rate around the perihelion passage of the comet, assuming meteoroids to be ejected from the nucleus over a wide range of directions, would fill a two-dimensional ecliptic cross section covering more than an hour (over 100 000 km) of the Earth's path. This relates to the overall ZHR increase towards the storm peak. The condition of reaching the ecliptic on 1999 November 18 tightly constrains the orbital period of meteoroids immediately after ejection, but this condition alone

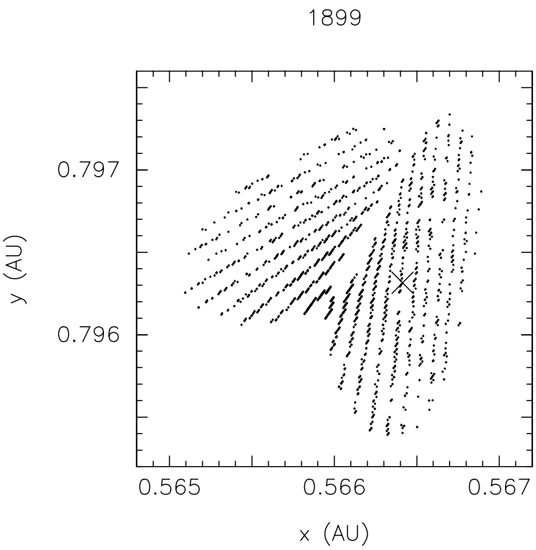

Figure 3. Descending nodes in 1899 of particles with the correct orbital period to reach the ecliptic in 1999 mid-November, with the node of the comet shown as a cross (from a Monte Carlo simulation). The meteoroid production rate is assumed uniform in true anomaly for heliocentric distance $r < 3.4$ au. The mean ejection speed is $25/r\,\mathrm{m\,s^{-1}}$ (uniformly random between 0.5 and 1.5 times this value). Ejection is in the given direction from a rotating source (period 10 d).

does not constrain meteoroids to any narrow region within the overall cross-section that would give the observed variations on time-scales such as 7 min. Other constraints would be to have (i) preferred times during the many months of meteoroid production, when the comet suddenly and briefly became more active, or (ii) preferred direction(s) of ejection, corresponding to jets of material being released, from the rotating nucleus. Regarding possibility (i), having meteoroids ejected only at a single value of the true anomaly of the comet, together with the orbital period constraint, but still allowing a wide range of ejection directions, forces the descending nodes of the resulting orbits to lie on a one-dimensional curve within the two-dimensional cross-section. A brief peak in the ZHR would occur when the Earth cut across the one-dimensional curve. However, this involves an assumption that β (the ratio of the forces of radiation pressure and solar gravity) is single-valued. In reality, there would be meteoroids over a range of sizes, with a range of β.

We therefore consider the possibility (ii) of a preferred direction of ejection from a rotating nucleus. A rotation period of the order of a day would be in accord with other periodic comets. Some Monte Carlo simulations show that having meteoroids ejected in a single direction from a rotating nucleus, together with the orbital period constraint, but allowing the ejection speed to be a free parameter, causes structure to appear in the cross-section (i.e. a two-dimensional region is not completely filled). Longer rotation periods (e.g. a few to several days) allow greater structure; shorter rotation periods tend to make descending nodes of meteoroids spread out to fill the whole two-dimensional cross-section. If having a range of β-values tends to spread meteoroids throughout the cross-section, jointly applying constraints of preferred ejection direction(s) and time(s) will still be able to restrict meteoroids to more compact regions (see Fig. 3). The number of free parameters (axis and period of rotation, meteoroid production rate, ejection speeds) makes it hard to determine a unique solution, but realistic physical mechanisms appear to exist to produce the structure in the activity profile that has been observed. An alternative to create (non-periodic) structure in the ZHR profile would be the fragmentation of the larger meteoroids released from the nucleus. Overall, the data obtained during the 1999 Leonid storm is evidence for variations in activity through a single perihelion passage (in this case 1899), and illustrates the value of high-resolution flux profiles.

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