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Leonids 2006 observations of the tail of trails: Where is the comet fluff?

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In 2006, Earth encountered a trail of dust left by comet 55P/Tempel-Tuttle two revolutions ago, in AD 1932. The resulting Leonid shower outburst was observed by low light level cameras from locations in Spain. The outburst peaked on 2006 Nov. 19d 04h39m +/- 3m UT (predicted: 19d04h50m +/- 15m UT), with a FWHM of 43 +/- 10 min (predicted: 38 min), at a peak rate of ZHR = 80 +/- 10 /hr (predicted: 50 - 200 per hour). A low level background of older and brighter Filament Leonids (χ ~ 2.1) was also present, which dominated rates for Leonids brighter than magnitude +4. The 1932-dust outburst was detected among Leonids of +1 magnitude and up. These outburst Leonids were much brighter than expected, with a magnitude distribution index χ = 2.60 +/- 0.15 (predicted: χ = 3.47 and up). Trajectories and orbits of 24 meteors were calculated, most of which are part of the Filament component. Those that were identified as 1932-dust grains did not penetrate less deep than Leonids in past encounters. We conclude that larger meteoroids than expected were present in the tail of the 1932-dust trail and meteoroids did *not* end up there because of low density. We also find that the radiant position of meteors in the Filament component scatter in a circle with radius 0.39 degrees, which is wider than in 1998, when the diameter was 0.09 degrees. This supports the hypothesis that the Filament component consists of meteoroids in mean-motion resonances.

Keywords: Meteoroids; Meteor Shower - Individual: Leonids; Comet dust trail; Comet - Individual: 55P/Tempel-Tuttle

1. INTRODUCTION

McNaught & Asher (1999a) first calculated that in November of 2006 (and again in 2007) the Earth would cross the two-revolution old dust trail of comet 55P/Tempel-Tuttle, which originated from the comet's 1932 return to the inner solar system. Meteors were expected to radiate from a geocentric radiant at R.A. = 154.32º, Decl. = +21.09º (J2000), in the constellation Leo, with a speed of $V_g = 70.80$ km/s.

The comet itself had passed Earth in 1998, and the 2006 shower would be caused by meteoroids ejected in an orbit significantly different from that of the parent comet. This is illustrated in Figure 1, which is a model of the dust trail at the time of encounter (Vaubaillon 2004, see below). The initial orbit of the meteoroids differed from that of the comet (a = 10.34 AU) by at least $\Delta a = 0.94$ AU. To achieve that much difference, the particles must either have been ejected at unusually high terminal speed of 88.3 m/s, if ejection is at perihelion in forward direction of comet motion (Maslov 2006, Sato 2006), or have been pushed outward more than other grains by solar radiation pressure due to a high surface-to-mass ratio (Kresák 1976).

If the position of the grains in the tail of the trail, so to speak, was caused by their morphology, then the corresponding meteors were expected to be faint, crumble more easily, and penetrate less deep in Earth's atmosphere than Leonids seen before, because a high surface-to-mass ratio implies small, low density, or unusually shaped meteoroids. This could manifest as a high magnitude size distribution index (number ratio of meteors in neighboring magnitude intervals), predicted to be $\chi = 3.47$ (Vaubaillon 2006), or the meteors could have unusual light curves peaking early in their path. If they would break more readily, the meteors might also show an early release of the volatile minerals containing sodium (Borovicka et al. 1999, Trigo-Rodríguez et al. 2004, Jenniskens 2006).

The model calculations by Vaubaillon (2004), at first, did not find any particles intersecting Earth's path; only after including small 0.1 - 0.2 mm radius particles in the model (+6 to +11 magnitude Leonids) were meteoroids found far enough dispersed along the trail to be observed (Figure 1). Meng (2005a, b) predicted a magnitude size distribution index as high as 63, making visual observations of the outburst all but impossible. Maslov (2006), too, warned that most meteors would be beyond the visual brightness range, recommending telescopic and radar observations instead. Unfortunately, radar observations are not efficient for detecting fast Leonid meteors due to the rapid diffusion of electrons at the high altitudes where these meteors occur.

Only the fact that a Leonid outburst was seen in 1969, under similar circumstances, gave confidence that an outburst ought to be detected. The dust encountered that year had a similar orbital period difference of 0.90 yr, with Earth passing at a similar +0.00005 AU from the center of the trail. The 1969 Leonid outburst was an earlier crossing of the 1932-dust trail, when it was only 1 revolution old. Observed rates peaked at ZHR = 400 ± 50 /hr with magnitude distribution index $\chi = 2.96 \pm 0.11$ (Millman 1970, Jenniskens 1995).

With the trail in 2006 now being stretched out by a factor of two (orbital period differences being cumulative), and with Earth passing again near the center of the trail, McNaught & Asher (1999a) put the anticipated peak rate at ZHR ~ 150 /hr. With a predicted encounter time of 04:50 ± 15 minutes UT, the 2006 outburst was expected to be visible in Western Europe, Western Africa and the tip of Brazil. Observers in Spain would be close to the center of the Earth's path through the stream during the crossing. The peak time would be 7 minutes earlier in E. Brazil and 6 minutes later in Scandinavia due to a different position of the observer in the trail (McNaught & Asher 1999b, McNaught 2006).

These predictions for 2006 were confirmed by Lyytinen and van Flandern (2000) and Vaubaillon (2006), who expected a peak time of 04:50 and 04:58 UT, respectively, and predicted peak rates of 50/hr and 200/hr from their empirical dust distributions calibrated to the 1969 data. More recently, Maslov (2006) estimated a peak rate of about 35/hr and a peak at 04:55 UT, but also a Full-Width-at-Half-Maximum of FWHM = 9 hours. Based on the observed change in shower duration with distance from the center of the trail, Jenniskens (2006) predicted a FWHM = 38 minutes instead.

This was the first encounter with a comet dust trail that was widely announced on a CBET prior to the event (Jenniskens et al. 2006a). We set out to observe this encounter with a range of low light level cameras, in the hope of detecting the outburst among faint +5 to +7 magnitude Leonids. The outburst manifested much as expected and first results were reported in a second CBET that was issued shortly after the campaign (Jenniskens et al. 2006b).

2. OBSERVATIONS

2.1. Intensified video observations.

Because of best prospects of clear weather, we chose two main observing sites in southern Spain. At Orgiva (3.4360º W, +36.9125º N), located south of the Sierra Nevada and south of the city of Granada, two intensified cameras were operated (PJ). Camera Orgiva#1 contained a Mullard XX1332 image intensifier with Canon FD f1.2 55-mm focal length lens and was aimed at azimuth (from North) Az = 354º and elevation H = 56º, recorded on a Panasonic NV-DS5 digital camcorder (Mini DV format), for a 33 x 25º field of view and a +7 meteor limiting magnitude. There was essentially no vignetting, but the star images were slightly out of focus at the edge of the field. Orgiva#2 sported an AEG-1400 image intensifier with a Canon f1.2/55-mm lens and was aimed at Az = 78º and H = 58º, recorded on Sony HDV 1080i camcorder (Mini DV, 1080i format), for a 21 x 12º field of view and limiting magnitude of +8. Both intensified cameras were equipped with a 600 lines/mm transmission grating for meteor spectroscopy. The observations at Orgiva were supported by a team of three experienced visual observers of the Dutch Meteor Society (KM, MV, and CJ), and two photographers (JLV, PB).

At the second station in Baza (2.73050º W, +37.56156º N), which is located north-east of the Sierra Nevada at a distance of 63 km, three intensified cameras were deployed for multi-station imaging. Baza#1 (operator: RH) consisted of an Mullard XX1332 intensifier, equipped with a Canon FD f1.2/55-mm lens, with a f.o.v. of 45º x 34º, aimed at Az = 293º, H = 62º, results of which were recorded on a Panasonic NV-DA1 digital Mini DV camcorder. There was significant vignetting, but the star imagers were sharp across the field. This camera was pointed in a co-located area multi-station with Orgiva#1. Baza#2 (operator: CTK) consisted of a Mullard XX1332 intensifier, equipped with a 50-mm f1.2 lens, aimed towards Az = 354º and H = 63º, results of which were recorded on a Sharp VL-PD6 Mini DV camcorder. This camera was pointed in a co-located area multi-station with Orgiva#2. A third wide angle camera, Baza#3 (CTK), consisted of a Mullard XX1332 intensifier, equipped with a Canon FD 1.4L/24 mm lens, and recorded on a Panasonic NV-DS5 camcorder in Mini DV format.

Some hours later, in California (121.4988º W, +36.7602º N), MK operated two intensified cameras from Fremont Peak Observatory, in order to measure the flux of the shower post outburst. He used Mullard XX1332 tubes with Canon FD 50-mm f1.4 optics and recorded the intensified image with a Sony TRV66 camcorder in Hi-8 analog NTSC format.

2.2. Low-light-level observations

In nearby Cerro Negro (near Seville, Spain: 06.33º W, +37.67º N), DM operated three low-light-level Watec 902H CCTV cameras with wide-angle optics for detection of relatively bright Leonids (+2 and brighter), with automatic detection and direct ditigal recording to PC. Cerro Negro#1 had a 6-mm f/0.85 lens with 56.7º x 43.4º f.o.v. and centred at altitude = 30_and Azimuth = 90º (East), Cerro Negro#2 was equipped with a 4.5-mm f/1.2 lens, for a wide 81.6 x 60.4 degree field of view, centred at altitude 60º, Az = 180_, while Cerro Negro#3 had a 2.6-mm f/1.0 lens for a 122.8º x 97.1º f.o.v., centred at altitude 60º, Az = 90º.

3. RESULTS

3.1. Flux measurements.

For the big picture, Figure 2 shows the Zenith Hourly Rates over the period November 16 - 20, as reported by the International Meteor Organization shortly after the campaign (Arlt & Barentsen 2006). A narrow outburst was observed at the anticipated time, identified as the 1932-dust trail encounter. This is not an independent observation, because much of this data is from the same visual team at Orgiva. Many ground-based observers elsewhere in western Europe were clouded out.

The outburst was observed under clear weather conditions at Baza and Orgiva, as well as at Cerro Negro. Orgiva was partially clouded only between about 05:30 and 05:48 UT towards the end of the observing interval, with observations ending due to morning twilight at 05:53 UT. A waning crescent Moon did not interfere with the observations. Only 2% of the Moon's visible disk was illuminated, and the Moon rose only 1.4 hours before the Sun. All cameras operated nominally, except for Baza#2, which suffered from condensation on the lens from dew at the time of the outburst, leaving only Baza#1 for two-station observations with Orgiva.

From Figure 2, we conclude that the outburst sits on top of a background of other Leonid shower activity. In 2006, the 1932-dust trail crossing happened 1 day after the annual shower peak, so that the annual shower component (Jenniskens 1996) does not account for much of this background (Fig. 2 and 3, dashed line).

In recent years, Leonid shower flux profiles usually contained a Filament component shaped like a Lorentzian distribution, with a FWHM of 0.8º, and rich in bright meteors (Jenniskens and Betlem 2002). Indeed, the elevated rates outside the narrow outburst from the 1932-dust trail crossing can be explained by such a Filament component with χ = 2.1 _ 0.1 (dotted line). We have a best fit for a peak rate of ZHR = 15 /hr at solar longitude 236.10 _†0.08º. This component has come down from its peak of ZHR = 206 _†20 /hr at the time of the 1998 comet passage, when it dominated the Leonid shower flux (Jenniskens 2006, Tab. 4b).

The three visual observers at Orgiva obtained the counts plotted in Figure 3 (marked "visual"). Magnitudes are compared to those of stars, seen by the night-adapted naked eye. The sky star limiting magnitude was estimated at +6.3 by Carl Johannink and +6.7 by Koen Miskotte, close to ideal circumstances (+6.5). A Lorentzian curve fitted to the data gives a FWHM = 0.030 _†0.007º (which corresponds to 43 _†10 minutes), a peak at 236.610 _†0.002º solar longitude (04:39 _†00:03 UT), and a peak rate of ZHR = 80 _†10 /hr. Indeed, Arlt & Barentsen (2006) put the peak time at 4:46 _†6 minutes UT, with a maximum ZHR = 75 _†8 /hr.

Each meteor of Orgiva camera 1 (coincident with Baza#1) and Baza camera 2 (coincident with Orgiva#2) was plotted on a star chart to confirm association with the Leonid shower. A total of 80 Leonids and 49 other meteors were detected by Orgiva#1 that had their end point inside the camera field between 3:30 and 6:00 UT. Baza #2 obtained 112 such Leonids and 74 others in the same time interval, while Orgiva#2 had 124 Leonids and 45 others (about 30 meteors in common). In addition, Baza#3 contained 120 Leonids and 52 others, for a total of 436 Leonids and 220 others for all cameras.

Figure 3 ("video") shows the rate of meteors from these cameras combined, averaged over 5 minute intervals. Each rate is expressed in terms of Zenith Hourly Rate (Jenniskens 1994). Most of our video meteors are faint +3 to +7 magnitude.

The brighter meteors recorded by the Cerro Negro observations (Fig. 3, "CCTV") showed a nearly constant activity throughout the night (Figure 3), suggesting that the bright < +0 magnitude members were essentially produced by the broader Filament background. Some bright meteors were part of the outburst. The photographic observations at Orgiva yielded six meteors of magnitude -2 to +1 at 04:03, 04:14:27, 04:14:44, 04:21, 04:37, and 04:41 UT, but not at other times in the night. Hence the outburst stood out from the background well for meteors of at least +1 and brighter.

3.2. The magnitude distribution.

The slope of the magnitude number distribution does not depend much on the exact definition of the magnitude, but for a meaningful comparison of magnitudes and meteoroid masses, it is important to understand what measure of brightness is being recorded. Our magnitudes were derived from a visual impression of the meteors on the sky or on the tapes, by comparison to the magnitude of stars. The Johnson V magnitude of stars was taken as the calibration. The intensified cameras have a wider response curve (390 - 880 nm) than the Johnson V band, or the night-adapted naked eye (420 - 580 nm), which can introduce some uncertainty in the reduction of the video magnitudes if not properly accounted for. Even then, these visually derived magnitudes from video tapes (m_v) were found to be 1.9 magnitudes fainter than those derived by integrating the meteor images and by making a photometric comparison to the stars in the video frames (m_p). Presumably, because the meteors form small dashes rather than points, which appear less bright than a point source of similar integrated brightness in the video frames. All magnitudes were corrected for distance to the meteor, into an "absolute" magnitude valid for a distance of d = 100 km, usually in a statistical manner with a constant correction for all meteors observed in a given camera field. In the case of multi-station orbits, the aparent magnitude was corrected to absolute magnitude by using the calculated distance to the meteor.

Each video camera is an independent measurement of meteoroid influx. In Figure 4, we plot these measurements of all cameras as a function of absolute magnitude m_v, together with those derived from the visual observations. The influx is the mean rate of all Leonids between 3:30 UT and 6:00 UT, and was derived from the magnitude distribution, corrected for detection probability, the net observing time, and the effective observing area.

The observing probability of retrieving meteors from video is given by Holman & Jenniskens (2002), and is essentially one for all meteors 2 magnitudes brighter than the limiting magnitude of the camera. It falls of to about 0.5 for meteors 1 magnitude brighter than the limiting magnitude of the camera. We consider only meteors that end in the field of view. Hence, only the faintest magnitude bin is uncertain because of detection probability. In contrast, visual observations can be uncertain over the faintest three magnitude intervals (+4 to +6) because of uncertainties in the probability function Jenniskens (1994). Those visual results should be given lower weight.

The solid line in Fig. 4 is a sum of this 1932-dust trail plus Filament component. A Filament component (dotted line), with an adopted χ = 2.1, dominates the rate for magnitudes brighter than +4 magnitude. The outburst Leonids were fainter, but not by much. We have χ = 2.60 _†0.15. Indeed, Arlt & Barentsen (2006) found that the activity peak coincided with a maximum in the population index of χ = 2.46 +/- 0.14, for both Filament and outburst peak combined (Arlt & Barentsen 2006).

All results point to a relatively small difference in the particle size distributions of the 1932-dust and that of the underlaying background. For the three visual observers combined, we have χ = 2.77 _†0.15 before 03:00 UT and χ = 2.82 _†0.05 during the outburst. The sporadic meteors had χ = 4.67 _†0.15. All these values are slightly overestimated due to uncertainties in the probability function.

3.3. Meteor trajectories and orbits.

Between 3:30 and 6:00 UT, twenty-four Leonids were detected well by both the Baza and Orgiva stations on more than four frames. Trajectories and orbital elements were calculated for each (Table I). These meteors had apparent brightness of +0.0 to +5.5, but when the signal of each image was integrated and magnitudes were corrected for distance, the absolute peak brightness was in the range -3.5 to +2.6 magnitude. A significant number must pertain to the 1932-dust outburst peak, because the video record showed a clear increase of rates (Fig. 3).

Astrorecord by de Lignie (1997) was used to measure the position of the meteor in the reference frame of background stars, and *FIRBAL* by Zdenek Ceplecha (Ceplecha et al. 1979) was used to calculate the trajectory of the meteor from fitting planes to the meteor path on the sky as seen by both stations. The orbital elements were calculated using *METOBS* by Langbroek (2004).

The observational error in the radiant position depends on the length of the measured trail (number of breaks N, Table I), and is better for brighter (longer) meteors and higher convergence angles. The convergence angle between the two planes intersecting the meteor parth and each of two stations was in the range Q = 35 - 57_. Based on similar three-station results in the past, we had an average error of 0.27_ in Right Ascension and 0.19_ in Declination (cross in Fig. 5), which should be valid for all but the brightest meteors in the sample. The radiant position uncertainty of the brightest meteors should be less.

The velocity uncertainty was calculated from the dispersion of meteor speeds among all individual frames in which the meteor position could be measured. The actual error is less than this, because the individual measurements are not independent. Hence, the standard error in the mean value is given, divided by the square root of the number of breaks.

Finally, the uncertainty in the height measurement is ~ 0.1 km, but uncertainty in where the meteor begins and ends can increase this error in height to ~ 2.6 km (1 break) or larger.

Figure 5 shows the radiant positions, after correction to a common position of Earth (λ_o = 235.0_, using a radiant drift of ΔR.A./$\Delta\lambda_o$ = +0.659 _/_ and ΔDecl./ $\Delta\lambda_o$ = -0.325 _/_).

Results are compared to those from the 1999 Leonid meteor storm (1899-dust trail) and model calculations (see below).

All bright Leonids ($m_v < +3$ magn.), presumably part of the Filament component, scatter wide around the predicted radiant for post-perihelion ejection (x), with no central condensation of the distribution. Even the radiant dispersion for fainter meteors is significantly larger than our nominal uncertainty and does not show the concentration of positions expected for a Gaussian distribution from observational errors.

3.4. Meteoroid penetration depth.

Figure 6 shows the beginning and end height of the Leonids as a function of absolute meteor magnitude (m_v). In the left graph, the results are compared to 3-revolution old 1899-dust Leonids observed during the 1999 campaign (Betlem et al. 2000, Spurny et al. 2000). The observing conditions in 1999 were very similar to those in 2006 and similar cameras were being used (Betlem et al. 2000). In the right graph, results are compared to the older Filament dust that dominated the 1995, 1998, 2001, and 2002 observations in the DMS video database.

The penetration depth of Leonid meteoroids encountered in 2006 was higher than those seen in 1999. Hence, the meteoroids were not more fragile than those encountered in 1999. The meteors were also detected earlier. Instead, the beginning height and end height are the same as that of past Filament meteors (Fig. 6, right).

3.5. Meteor light curves and spectra.

Three Leonid spectra were recorded by the two dedicated cameras at Orgiva, but they were too faint for analysis. Hence, we could not evaluate the relative loss of sodium versus magnesium as a function of altitude.

The light curves from all multi-station meteors are shown in Figures 7a and 7b. To guide the eye, we plotted in each graph a dashed line showing the light curve expected for a solid body in the NRLMSISE Standard Atmosphere ρ_a. This curve is given by (McKinley 1961):

$$I = I^{max}\, 9/4\, \rho_a / \rho_a^{\ max} \, (1 - \rho_a / 3\, \rho_a^{\ max})^2 \qquad (1)$$

where $\rho_a^{\ max}$ is the air density at the point of peak brightness I^{max}. $\rho_a^{\ max}$ was matched to correspond to the measured end height. I^{max} was taken as a free parameter and matched to the peak of the observed light curve.

Fragmentation sets on when the Leonid meteoroids are heated high enough to evaporate meteoric metals, normally at an altitude of 120 - 136 km. Due to this fragmentation, the shape of the light curve deviates from that of Eq. (1). The shape has traditionally been expressed either in terms of the position of the peak of the curve in terms of symmetry parameter F, which is defined as the ratio of the distance to the point of maximum brightness to the entire length of the curve:

$$F = (\text{height peak} - \text{height beginning}) / (\text{height end} - \text{height beginning}) \qquad (2)$$

where the beginning is chosen as the onset of rapid evaporation and the end at that same meteor's brightness level.

Or in terms of the skewness of the shape of the profile. That skewness can be expressed in terms of how the particle breaks (either in many small pieces, or a few larger ones), by assuming instantaneous fragmentation into an exponential distribution of masses, with an upper and lower limit, and by subsequently calculating a composite light curve from a cluster of particles with differential mass distribution s. We adopted the light curve shapes calculated by Murray et al. (2000) to express the skewness of the profile.

The parameters for F and s of each curve are tabulated in Table I. We have a mean <F> = 0.54 _†0.08 and <s> = 1.75 _0.22Æ¶The differential mass distribution index, s, would translate to χ = 2.0 _†0.4, a typical value for a collisional cascade, and the same as the particle size distribution in the Leonid Filament component as a whole (Jenniskens 2006, p. 94).

This compares to <F> = 0.62 _†0.15 for the 1999 Leonids and <F> = 0.48 _†0.14 for the 1998 outburst caused by the encounter with the 1899-dust trail at high heliocentric distance (Murray et al. 2000, Jenniskens 2006). The very low values of F ~ 0.2 that were common during the 1998 outburst are not observed here. In comparison, Murray (2005) measured <F> = 0.57 _† 0.01 (1999) and <F> = 0.58 _† 0.01 for the 2001, 1767-dust. Hence, compared to Murray's data for 1999 and 2001, the 2006 Leonids were *not* significantly more skewed towards the beginning.

The lack of meteoroids with an early peak in the light curve, such as those observed during the 1998 encounter with the 1899-dust trail, is remarkable. One example would be meteor 04:18:04 UT (Fig. 7a). A second example was a meteor photographed at Orgiva close to the Leonid shower radiant at 04:41 UT (Fig. 8). This was a bright +0 magnitude Leonid and it would be quite remarkable if this meteoroid was part of the 1932-dust trail.

4. DISCUSSION

4.1. Empirical dust distribution in a 1-revolution comet dust trail.

What do the models predict? The pioneering work by Kondrat'eva and Reznikov (1985), McNaught & Asher (1999a), and Lyytinen (1999) made it possible to calculate the encounter time of the dust trails by calculating the center position of the trail as a result of planetary perturbations. They resorted to empirical distributions of dust in the 3 dimensions of the trail in order to predict the duration and peak activity of a shower: in the Earth's path (expressed as solar longitude: λ_o), in the direction of the Sun (expressed as heliocentric distance: Δr), and along the comet orbit (expressed as difference in semi-major axis of the initial orbit: Δa), derived from comparing the observed shower activity during past trail crossings with those expected from simple geometric distributions.

Figure 9 shows the dust density in the trail calculated from the observed peak Zenith Hourly Rate of the outburst component only (ZHR = 80 /hr), after correction for the dilution factor f_m calculated in the model, and the dependency on how the dust falls off away from the trail center $f(\Delta r)$, according to Jenniskens (2006, Fig. 15.33):

$$f(\Delta r) = 10^{-1450*(\Delta r-0.00077)} \tag{3}$$

where the offset factor is 0.00025 AU if the method of Kondrat'eva and Reznikov is used. The new observations plot close to the data for the 1969-dust trail crossing, in good agreement with these past observations.

This result establishes that the 1969 calibration is essentially correct. Hence, the empirical distributions used in recent years to describe the dust distribution in the 55P/Tempel-Tuttle dust trails is valid also for large distances from the comet. The empirical relationship for the width of the trail as a function of heliocentric radial distance by Jenniskens (2006) does agree with the observations, while some theoretical relationships for the width can be dismissed (Lyytinen & Van Flandern 2000, Maslov 2006). The empirical estimate for the magnitude distribution index by Meng (2005a,b) is not correct at these large distances away from the position of the comet.

4.1. Calculated dust distribution in a 1-revolution comet dust trail.

It is much more involved to calculate the expected distribution of dust in a dust trail. That depends on the adopted model for the initial ejection speed and direction and the subsequent effect of solar radiation pressure on the particle orbits, which depend on meteoroid mass, density, and morphology (Kresák 1976, Kimura et al. 2002). In order to do so, a meteoroid dust trail model was created using methods described in Vaubaillon et al. (2005a, b). 250,000 particles were ejected on the sun-lit hemisphere in isotropic direction spread along the orbit of the parent comet 55P/Tempel-Tuttle during the 1932 return, with the rate of ejection according to its measured activity profile in the 1998 return, using the ejection model by Crifo and Rodinov (1997), which is closely based on that of Whipple (1951). The model predicts the ejection speed of a particle of given size and density. We assumed a meteoroid density of 0.97 g/cm^3 (Spurny et al. 2000).

Five groups of particles in the diameter range d = 0.2 to 1 mm, d = 1 - 2 mm, d = 2 - 10 mm, d = 10 - 20 mm, and d = 20 - 200 mm were considered, with particles in each group of size being distributed according to a power law inside the size interval. In this way, we can visualize the distribution of meteoroids in all five magnitude classes, despite the fact that meteors of size 20 mm are much rarer than meteors of size 1 mm.

The planetary perturbations on each ejected particle were rigorously calculated. 47 particles were found to be near Earth's orbit (at less than 0.007253 AU) in a _†6.5 day period around 2006 November 19 04:50 UT (when Earth was at X = 0.5436, Y = 0.8254 AU) were then selected. There is no overlap of other recent dust trails of comet 55P/Tempel-Tuttle (Fig. 10). The minimum heliocentric distance is $\Delta r = +0.00088$ AU, meaning that the Earth crossed through the center of the dust trail.

The model does not predict correctly the width of the stream for these meteoroids. Figure 3 (graph most to the right) shows the nodal distribution predicted for the faint +11 to +6 magnitude Leonids that have high enough ejection speed to make it this far out in the trail. Note that the width of the observed distribution is much narrower than that predicted for the fainter meteors. Hence, if the ejection conditions are such that they can be put in this part of the trail, then they also tend to scatter too wide. Whatever mechanism is responsible for bringing the grains this far out in the trail, has to keep the nodal dispersion small.

The mean offset in semi-major axis for all particles at Earth orbit was calculated to be $\Delta a = 1.7643$ AU (Fig. 9). This value for Δa is about twice that calculated from the method of Kondrat'eva and Reznikov (1985), which would give $\Delta a = 0.97$ AU ($\Delta r = +0.00013$ AU and $f_m = 0.466$) (McNaught and Asher 1999a, Maslov 2006). No such large disagreement exists for dust encountered closer in to the comet. This difference in Δa makes it hard to plot the new activity calibration in Figure 9. The two alternative positions are both plotted. In addition, the particles were found compressed in this section of the dust trail, with a dilution factor $f_m = 0.90$, higher than the expected $f_m = 0.5$ for a 2-revolution dust trail and higher than the value of 0.466 calculated before.

The observed dust distribution along the comet orbit for meteors of magnitude +3 to +6 is that in the model for sizes d = 1 - 2 mm. The corresponding magnitude interval has to be calculated from an adopted mass-luminosity relationship. At the time of the peak, the Leonid radiant was at 61_ elevation, while Leonids had an entry speed of V = 71.45 km/s. From most recent luminosity estimates by ReVelle and Ceplecha (2001), Jenniskens (2006) derived for such Leonids:

$$\log M\ (g) = -0.94 - 0.40\ m_p \qquad (4)$$

For a density of 0.97 g/cm^3, 1 - 2 mm diameter meteoroids would give a meteor magnitude of +11.1 to +5.9 magnitude. This would mean that only Leonids of visual magnitude +6 and fainter should have been present in the meteor outburst. Instead, we can see a significant increase of meteors as bright as magnitude +1 during the outburst (radius ~ 1 cm). There are many reasons why the ejection speeds may not be correct (e.g., Jones 1995).

The magnitude scale is about 1 magnitude lower if we adopt the alternative equation by Brown et al. (2000), who derived from the luminosity efficiency parameter of Verniani (1965):

$$\log M\ (g) = -1.98\_0.02\dagger - 0.43\_0.01\dagger m_p \qquad (5)$$

Eq. 5 then translates the size range in group I to a meteor magnitude range of +7.9 to +3.1 photometric magnitude, or +9.8 to +5.0 visual magnitude. This suggests strongly that the problem is not the uncertain mass-luminosity relationship.

The radiant distribution may be a clue to the origin of this dust (Fig. 5). It is surprisingly difficult to discriminate the 1932-dust grains from those of the Filament. The brighter (and more precise) meteors have radiants that are distributed in a circle of radius = 0.39_, centered on R.A. = 153.86_, Decl. = +21.36_ (at solar longitude 235.0_, J2000). In 1998, the Filament was the dominant contribution to the Leonid shower and we found that the radiant positions were also scattered in a circular radiant distribution, this time with a radius of only about 0.09_ (Betlem et al. 1999, Jenniskens 2006, Fig. 15.11). For that reason, we suspect that these brighter meteors are part of the Filament component. If so, then these observations are strong support for the hypothesis that the meteoroids are in a mean motion resonance. Further theoretical work may identify exactly what is the mechanism responsible for Filaments of Halley-type comets.

The fainter half of our meteors (gray diamonds) scatter around the predicted radiant position (crosses) for the 1932-dust trail. However, the distribution covers the full range in Right Ascension, rather than being concentrated near the center as would be expected from observational errors alone. The model identifies all five outlayers in the model as dust ejected more than 60 days from perihelion. This dust does not have anomalous ejection speeds (range 20 - 50 m/s, while perihelion dust in the model was ejected at speeds of 15 - 80 m/s). There is also no anomalous direction of ejection. This could imply that much of the 1932-dust we encountered in 2006 was from dust ejected relatively far from perihelion. Perhaps, the comet may have ejected relatively more large dust grains in 1932 at high heliocentric distances than determined from the observed comet light curve in the most recent return (Watanabe et al. 2001).

After excluding all radiant positions that are near the Filament circle, and those that scatter so wide as to suspect that the meteoroids are part of the annual shower component, we are left with only four likely candidates for 1932-dust: 05:18:29 UT, 05:30:49 UT, 05:15:58 UT, and 04:26:47 UT, which have F = 0.56, 0.56, 0.54, and 0.44, respectively, and s = 1.70, 1.50, 1.70, and 1.90, respectively. Compared to the mean values of $F = 0.54$ and $s = 1.75$, these are normal parameters. Hence, the light curves of the 1932-dust grains did not stand out from those of the Filament. The meteors also do not penetrate less deep than other Leonids of the same brightness. These four meteors do appear to start shining slightly earlier in their trajectory (Fig. 6, open circles).

Where are the low density grains or grains with unusual morphological structure, the comet fluff so to speak? Their abundance should have been significantly higher in this part of the dust trail compared to past Leonid showers. Only one video and one photographic meteor were seen that had a rapid onset early in their path (at 04:18 and 04:41 UT), typical of those observed in the 1998 encounter with the 1899-dust at large relative heliocentric distance. Why are they not abundant in this part of the trail? Could it be that the most fluffy lower density grains are preferentially fragmented, either during ejection or later in the interplanetary medium (Watanabe et al. 2003, Trigo-Rodríguez et al. 2005)?

5. CONCLUSIONS

For our adopted mass-luminosity relationship, the Crifo dust ejection model does not fully describe the velocity distribution of ejected dust grains in the range 0.1 - 1 mm. A significant fraction of grains seems to be ejected with a higher initial semi-major axis difference Δa than predicted, either due to a higher ejection speed, a stronger effect of radiation pressure, or because more dust is ejected at large heliocentric distances than derived from the comet light curve. The distribution of 0.5 - 1 mm meteoroids along the comet orbit is like that of 0.1 - 0.2 mm grains in the model at this distant position in the tail of the trail.

The higher Δa most likely does not arise from lower particle densities, as the meteoroids we mostly likely identify as being associated with the 1932-dust trail do not crumble more easily and do not penetrate less deep in Earth's atmosphere than Leonids observed during the 1999, 2001 and 2002 dust trail crossings.

If the meteoroids are simply more heavy than thought, then we do not understand the relatively narrow width of the stream at this position in the trail, nor the observed relatively low magnitude distribution index ($\chi = 2.6$).

Our observations do reveal an important clue about the origin of the Filament component: We find that the meteor radiants scatter in a circular manner with a radius of 0.39_, wider than in 1998, when the meteors scattered in a circle with radius 0.09_.

6. FUTURE WORK

The implications for the upcoming return on 18 November 2007, when the Earth again will cross the 1932-dust trail close to its center at around 23:03 UT (Jenniskens 2006, Tab. 4a), include that a narrow peak of activity (FWHM ~ 0.68 hr) is expected at a rate of about ZHR = 32/hr (rather than 80/hr) on top of a background activity, with much the same magnitude distribution index as observed in 2006: $\chi \sim 2.6$ (rather than 3.48). This outburst will be best seen from China, India, and parts of Russia.

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REFERENCES

Arlt, R., and Barentsen, G., 2006. Bulletin 21 of the International Leonid Watch: Global analysis of visual observations of the 2006 Leoind meteor shower. JIMO 34, 163-168.

Betlem, H., ter Kuile, C., van 't Leven, J., et al., 1997. Precisely reduced meteoroid trajectories and orbits from the 1995 Leonid meteor outburst. Planet. Space Sci. 45, 853-856.

Betlem, H., Jenniskens, P., van 't Leven, J., ter Kuile, C., Johannink, C., Zhao, H., Lei, C., Li, G., Zhu, J., Evans, S., Spurny, P., 1999. Very precise orbits of the 1998 Leonid meteors. Meteoritics & Plan. Sci. 34, 979-986.

Betlem, H., Jenniskens, P., Spurny, P., et al., 2000. Precise trajectories and orbits of meteoroids from the 1999 Leonid meteor storm. Earth, Moon, and Planets 82/83, 277-284.

Borovicka,ÅJ.,Stork,ÅR.,Bocek,ÅJ.1999. First results from video spectroscopy of 1998 Leonid meteors. Meteoritics & Plan. Sci. 34, 987-994.

Brown, P., Campbell, M. D., Ellis, K. J., et al., 2000. Global ground-based electro-optical and radar observations of the 1999 Leonid shower: first results. Earth, Moon, Planets 82//83, 167-190.

Ceplecha, Z., Bocek, J., Jezkova, M., 1979. Photographic data on the BRNO Fireball (EN 140 977, Sep 14, 1977). BAC 30, 220-224.

Crifo, J. F., and Rodionov, A. V., 1997. The dependence of the cicumnuclear coma structure on the properties of the nucleus. Icarus 127, 319-353.

De Lignie, M., 1997. Astro record 3.0. Radiant, Journal of the Dutch Meteor Society, 19, 28-30.

Holman, D., and Jenniskens, P., 2002. Leonid storm flux from efficient visual scanning of 1999 Leonid storm video tapes. JIMO 29, 77-84.

Jenniskens, P., 1994. Meteor stream activity. I. The annual streams. Astron. Astrophys. 287, 990-1013.

Jenniskens, P., 1995. Meteor stream activity. II. Meteor outbursts. Astron. Astrophys. 295, 206-235.

Jenniskens, P., 1996. Meteor stream activity. III. Measurement of the first in a new series of Leonid outburst. Meteoritics & Plan. Sci. 31, 177-184.

Jenniskens, P., 2006. Meteor Showers and their Parent Comets. Cambridge University Press, Cambridge, U.K., 790 pp.

Jenniskens, P., and Betlem, H., 2002. Massive remnant of evolved cometary dust trail detected in the orbit of Halley-type comet 55P/Tempel-Tuttle. Astrophys. J. 531, 1161-1167.

Jenniskens, P., Meng, H., McNaught, R., and Asher, D., 2006a. Leonid meteors 2006. Green, D. W. E. (Ed.), CBET 710, 1-1 (October 2006).

Jenniskens, P., Miskotte, K., Vandeputte, M., Johannink, C., van 't Leven, J., Bus, P., ter Kuile, C. R., and Haas, R., 2006b. Leonid meteors 2006. Green, D. W. E. (Ed.), CBET 767, 1-1 (December 2006).

Jones, J., 1995. The ejection of meteoroids from comets. MNRAS 275, 773-780.

Kimura, H., Okamoto, H., and Mukai, T., 2002. Radiation pressure and the Poynting-Robertson effect for fluffy dust particles. Icarus 157, 349-361.

Kondrat'eva, E. D., Reznikov, E. A., 1985. Comet Tempel-Tuttle and the Leonid meteor swarm. Solar System Res. 19, 96-101.

Kresák, L., 1976. Orbital evolution of the dust streams released from comets. BAC 27, 35-46.

Langbroek, M., 2004. A spreadsheet that calculates meteor orbits. JIMO 32, 109-110.

Lyytinen, E., 1999. Leonid predictions for the years 1999 _†2007 with the satellite model of comets. Meta Res. Bull. 8, 33-40.

Lyytinen, E. J., and Van Flandern, T., 2000. Predicting the strength of Leonid outbursts. Earth, Moon, and Planets 82/83, 149-166.

McNaught, R. H., 2006. Visibility of Leonid showers in 1999-2006 and 2034. JIMO 27, 164-171.

McNaught, R.H., and Asher, D. J., 1999a. Leonid dust trails and meteor storms. JIMO 27, 85-102.

McNaught, R. H., and Asher, D. J., 1999b. Variation of Leonid maximum times with location of observer. Meteoritics & Plan. Sci. 34, 975-978.

Maslov M., 2006. Leonids 2006: prediction of activity. Website:
http://feraj.narod.ru/Radiants/Predictions/Leonids2006eng.html

McKinley, D. W. R., 1961. Meteor science and engineering. McGraw-Hill, New York, 309 pp.

Meng, H., 2005a. The mass distribution of the Leonids. Proceedings of the IMC, L. Bastiaens, J. Verbert, J. M. Wislez, C. Verbeeck, eds., Oostmalle 2005, International Meteor Organization, p. 117-129.

Meng, H., 2005b. The relationship between the semi-major axis, mass index and age of the Leonid meteor shower. MNRAS 359, 1433-1436.

Millman, P., 1970. Meteor news. J. Roy. Astron. Soc. Canada 64, 55-57.

Murray, I. S., Beech, M., Taylor, M. J., Jenniskens, P., and Hawkes, R. L., 2000. Comparison of 1998 and 1999 Leonid light curve morphology and meteoroid structure. Earth, Moon and Planets 82-83, 351-367.

Murray, I. S., 2005. A study of Leonid meteor light curve morphology, 1998 - 2002. M. Sc. Dissertation, The University of Regina, Regina, Canada.

ReVelle, D. O., and Ceplecha, Z., 2001. Bolide physical theory with application to PN and EN fireballs. ESA SP 495, 507-512.

Sato, M., 2006. National Astronomical Observatory Japan. Website: http://fas.kaicho.net/tenshow/meteor/55p2006/Leo2006.htm

Spurny, P., Betlem, H., van 't Leven J., and Jenniskens P., 2000. Atmospheric behavior and extreme beginning heights of the 13 brightest photographic Leonids from the ground-based expedition to China. Meteoritics & Plan. Sci. 35, 243-249.

Trigo-Rodríguez J., M., Llorca, J., Fabregat, J., 2004. Chemical abundances determined from meteor spectra - II. Evidence for enlarged sodium abundances in meteoroids. MNRAS 348, 802-810.

Trigo-Rodriguez, J. M., Betlem, H., and Lyytinen, E., 2005. Leonid meteoroid orbits perturbed by collisions with interplanetary dust. Astrophys. J. 621, 1146-1152.

Vaubaillon, J., 2004. Dynamic of meteoroids in the solar system. Application to the prediction of meteoric showers in general, and Leonids in particular. Ph.D. Thesis, I.M.C.C.E., l'Observatoire de Paris, Paris, France.

Vaubaillon, J., Colas, F., and Jorda, L., 2005a. A new method to predict meteor showers. I. Description of the model. Astron. Astrophys. 439, 751-760.

Vaubaillon, J., Colas, F., and Jorda, L., 2005b. A new method to predict meteor showers II. Application to the Leonids. Astron. Astrophys. 439, 761-770.

Vaubaillon, J., 2006. 2006 Leonids. I.M.C.C.E. Meteor Shower Ephemeris Server. Institute et de Calcul Ephemerides, Paris, France. Website: http://www.imcce.fr/page.php?nav=en/ephemerides/phenomenes/meteor/DATABASE/Leonids/2006/index.php

Verniani, F., 1965. On the luminous efficiency of meteors. Smithson. Contr. Astrophys. 8, 141-172.

Whipple, F. L., 1951. A comet model II. Physical relations for comets and meteors. Astrophys. J. 111, 464-474.

Watanabe, J., Tabe, I., Hasegawa, H., Hashimoto, T., Fuse, T., Yoshikawa, M., Abe, S., and Suzuki, B., 2003. Meteoroid clusters in Leonids: Evidence of fragmentation in space. PASJ 55, L23-L26.

Watanabe, J., Fukushima, H., and Nakamura, T., 2001. The activity profile of comet 55P/Tempel-Tuttle in 1998 return: Meteoroid release concentration on the perihelion. In: Proceedings of Meteoroids 2001 Conference, B. Warmbein, ed., ESA Publications

Submitted for publication in ICARUS.

Division, Noordwijk, the Netherlands, ESA SP-495, p. 175-178.