MORE ON THE DUST TRAILS OF COMET 55P/TEMPEL-TUTTLE FROM 2001 LEONID SHOWER FLUX MEASUREMENTS
(ESA SP-500)

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ABSTRACT

Recent Leonid storms traced the dust distribution in Earth's path through dust trails of comet 55P/Tempel-Tuttle that were deposited a number of orbits ago. Here, we present further considerations that help interpret the flux measurements in terms of the mean dust distribution in a one-revolution old trail, and the comet's dust ejection process. Predictions for the upcoming 2002 encounter are given.

1. INTRODUCTION

Recent meteor storm prediction models consider two aspects: 1) the ejection of particles from the comet and the subsequent radiation pressure, and 2) the influence of planetary perturbations on the particles. The first process determines how the dust will be distributed along the comet orbit after N revolutions. The second item determines how far those dust trails pass by Earth's orbit and at what time they will be encountered. The planetary perturbations can be precisely calculated for a given initial orbit, but the ejection process introduces so many free parameters and competing mechanisms with similar final results that a wide range of dynamically different orbits need to be calculated to create a good picture of the dust density near Earth's orbit.

The more ambitious Leonid storm models do just that [1-4]. As a result, they are computing-intensive and usually provide only sparse coverage of the available free parameter space. These models mostly help to understand useful relationships between the final position of dust particles in certain ejection and radiation pressure conditions [5], but predictions are unreliable.

Prediction models were validated only when the problem was reduced *ad infinitum* to studying the ejection of a single particle at perihelion (Fig. 1). Kondrat'eva and Reznikov [6], following earlier work started after the 1966 Leonid storm, discovered a general good agreement between the predicted time of the shower and the observed peak of an outburst. This method was popularized and worked out further by McNaught and Asher [7] and Lyytinen [8-9].

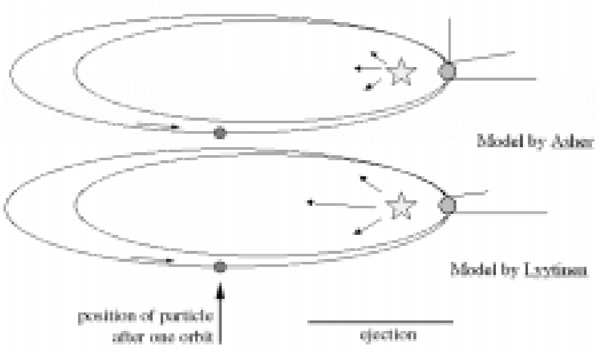

Fig 1. Schematic properties of meteor storm prediction models discussed in the text. [7,8]

It has since been confirmed that such simple assumptions can provide a fairly precise prediction of the position of a comet's dust trail near Earth's orbit N revolutions later. The orbit of only one particle needs to be calculated with just the right orbital period to end up lagging the comet by the right amount for a shower at a given date (Fig. 1). However, to accommodate planetary perturbations of the orbital period itself, a small number of particles with slightly different orbits trace better the position of the trail at the right encounter time.

Note that Lyytinen [8] and McNaught & Asher [7] use quite different initial conditions but arrive at the same result, because they calculate in essence the perturbations on the same particle orbit. Lyytinen assumes that the required lag between comet and particle is due to radiation pressure effects alone, while McNaught and Asher assumes a combination of radiation pressure and ejection speed (Fig. 1).

Three questions remain to be solved: 1) how is the dust distribution along the comet dust trail, 2) how large, if any, are deviations of the trail positions from those predicted with the simple initial conditions, 3) how do both relate to physical circumstances during comet ejection. If those questions are answered correctly, then it is possible to build a more complex numerical model and pin down the physical processes of ejection.

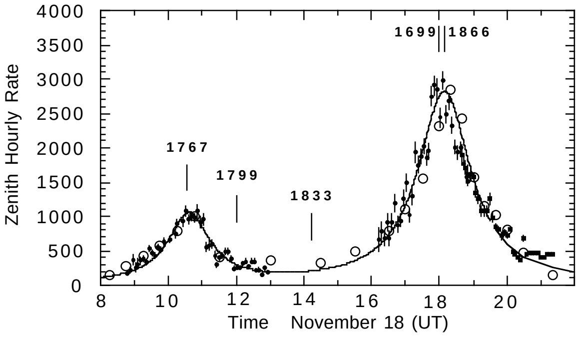

Fig. 2. Activity curve of 2001 Leonid storms (closed symbols Leonid MAC campaign, open symbols IMO data).

2. MEAUSRED DUST DISTRIBUTION

Recent Leonid storm observing campaigns have added a large sample of cross sections of dust density and particle sizes to mostly anecdotal evidence from past Leonid storms (Table I). Precise measurements of activity curves have greatly helped clarify the picture. Figure 2 shows the results from the 2001 Leonid Multi-Instrument Aircraft Campaign, based on (post-mission reduced) near-real time flux measurements from the FISTA aircraft (1767 dust trail only), and from two ground sites at Mount Lemmon Observatory (Arizona) and Alice Springs (Australia). The near-real time counts were obtained by tallying mouse-clicks from visual observers that watched different parts of the sky, or the video output of intensified cameras onboard the aircraft with video headset displays. Members of the Dutch Meteor Society complimented the data with ground-based observations from Beijing, China.

The first 2001 storm is a well-isolated encounter with the 1767 dust ejecta, but the second storm is a composite of the 1699 and 1866 dust trails (with a small contribution from even older trails). Meteor trails measured close to the radiant [10] suggest relative rates of 1699/1866 at about a 2-3 ratio. We can also set an upper limit to the 2001 activity from the 1799 dust trail encounter, predicted to be the dominant peak by Brown & Cook [2], but has only ZHR < 40 hr^{-1} (Table I).

The observed dust trail encounters need to be translated back to when the dust trail was only 1 revolution old. There are three spatial directions to consider: in the Earth's path ($\Delta\lambda_o$), along the comet orbit (Δa), and the perpendicular direction towards the Sun (Δr).

It is clear that the dust trail continues to stretch out along the comet orbit with each revolution. Indeed, the formation of the dust trail is in the first place due to a range in orbital period [11]. The particles that lag the comet most are the ones with the widest orbit. Hence, the measured dust density is in first approximation proportional to ZHR ~ 1/N, with N the number of revolutions. The measured dust density is also affected by perturbations on the orbital period, which cause some parts of the trail to stretch and others to compact. This factor is calculated by McNaught and Asher [7] and Lyytinen [8-9] and together with the 1/N factor called f_m, which is close to 1/N.

All other factors predicting the peak activity of the shower are a function of the dust distribution in the trail, $f(\Delta\lambda_o)$ and $f(\Delta a)$, and the calculated minimum distance from the trail center $f(\Delta r)$:

$$ZHR = ZHR_{max} * f(\Delta\lambda_o) * f(\Delta r) * f((\Delta a) \qquad (1)$$

where $ZHR_{max} = 6 \pm 1 \times 10^4\ \mathrm{hr}^{-1}$ is proportional to the peak dust density in the one-revolution tail, at a position some distance behind the comet itself (Δa_o) as a result of the effects of solar radiation pressure that tend to put the particles in a wider orbit than the comet.

Different functional forms have been proposed. Based on precise measurements from the 1999 Leonid MAC mission, Jenniskens et al. [12] found that the distribution in Earth's orbit is best represented by a Lorentz curve, rather than the Gaussian or exponential distribution that was assumed before:

$$f(\Delta\lambda_o) = (W/2)^2 / ((\lambda_o + \delta\lambda_o - \lambda^{max}{}_o)^2 + (W/2)^2) \qquad (2)$$

where $\delta\lambda_o$ denotes any deviation between predicted and calculated dust trail position. W is the full-width-at-half-maximum of the shower profile at the particular dust trail crossing. This function was subsequently adopted by Lyytinen et al. [13]. Leonid MAC measurements showed that the smaller particles have a wider stream profile, with possible small shifts in the peak activity, but all dust sizes have the strong Lorentz wings [14]. There is no strong change in the particle size distribution across the activity curve. The differential mass distribution in the dust trails is shallow ($s = 1.64 \pm 0.05$) and the mass-loss is dominated by the largest meteoroids [14].

A simple plot of width versus the calculated distance between stream center and Earth orbit (Δr) shows a smooth curve only if the initial width is mostly maintained and any subsequent widening is small, suggesting that all perturbations in a cross section of the dust trail remain the same. In more recent models that address possible accumulating effects of radiation pressure, Lyytinen et al. [9, 13] have the width increase with the number of revolutions. It is also assumed that there is a continuous acceleration over time, both thought to result from non-radial radiation pressure effects. In Brown's models [2], the dispersion increases in time as well, but for different reason: because particles making up a given cross section are in dynamically different orbits and planetary perturbations continue to increase the shower width.

Jenniskens [12, 14] first studied the variation of width with increasing miss distances Δr, and found an exponential increase, significantly more shallow than expected if the dust distribution was cylindrical:

$$W_E(\Delta r) = W \sin(18.1^o) = 1.2\ 10^{-4}\ \ 10^{+600^* |\Delta r+\delta r+0.00020|} \quad (3)$$

It was also found that the peak activity of the shower declined with increasing Δr in exponential manner, with an exponent twice as high, again implying that the dust distribution was not cylindrical [14]:

$$f(\Delta r) = 10^{-(1450\pm 100)\ |\Delta r + \delta r|} \quad (4)$$

Both profiles are not centered on the calculated position of the trails. There is a trend that profiles which are slightly too wide are also somewhat too narrow, as if the trails were displaced by an amount δr in anti-hellion direction from the calculated position. Usually, the displacement is small and it is clear that the Earth passed on the inside or the outside of the trail. Only the 1998 encounter with the 1899 dust trail and the recent 2001 encounter with the 1767 dust trail have a profile width that is consistent only with a passage on the other side of the trail. Indeed, both dust trails had recent encounters with Earth at this position, which can have displaced the trails significantly. The correct distance from the trail center is $\Delta r + \delta r$ (Table I).

I now introduce another possible improvement on the analysis. Earlier work [14] did not consider the shift of the peak further from the sun in subsequent revolutions (Δa_o*N), nor the wider dust dispersion along the comet orbit (W_a*N), in calculating the distribution of dust in the comet orbit $f(\Delta a)$. However, if one introduces those effects in the proposed Lorentzian distribution (the one that seemed to fit the data best), then it is possible to rewrite the equation so that the function is again a Lorentzian as a function of $\Delta a/N$, instead of Δa:

$$f(\Delta a) = f_m *(W_a/2)^2 / ((\Delta a/N-\Delta a_o)^2 + (W_a/2)^2) \quad (5a)$$

When ZHR $_{max}$ / $f(\Delta r)$ is plotted versus $\Delta a/N$, I now find a different functional shape with a more rapid decline in dust density in a forward direction from a maximum at Δa_o = 0.027±0.003 AU (Fig. 3). The function is best parameterized in log-log coordinates, as a second (or perhaps third) order polynomial:

$$f(\Delta a) = f_m *10\text{^}(-2.28-2.26*\log(\Delta a/N) \\ -0.064* (\log(\Delta a/N))^2 +0.29*(\log(\Delta a/N))^3 \quad (5b)$$

After introducing this equation, the residuals between observed and calculated activity decrease significantly. The shift (δ) introduced to account for those discrepancies is now nearly constant at a median δ = +0.00015 AU with standard dev. = ±0.00015 AU. The shift in node correlates with $\Delta r+\delta r$:

$$\delta\lambda_o \text{ (AU)} = -0.00015 - 0.2 * (\Delta r+\delta r) \quad (6)$$

except for the 1966 and 1969 encounters. This completes the new prediction formalism.

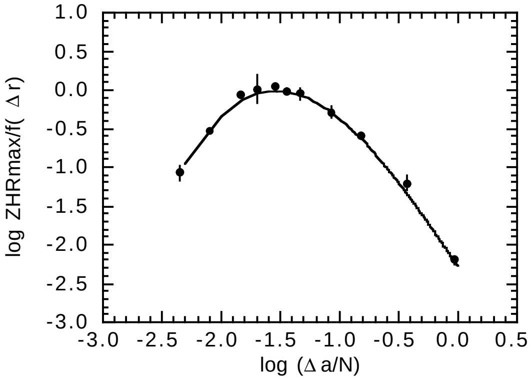

Fig.3. Dust density along the comet orbit.

3. IMPLICATIONS

In a previous paper [14], I proposed that comet dust fragmentation and ejection far from perihelion may explain the Lorentz shaped wings of Eq. 2. I was not surprised to find a similar symmetric dust distribution in the comet orbit. However, Eq. 5b differs from 5a in that the dust distribution falls off much more steeply from its peak in the forward direction of motion. This dust distribution would lower the total dust mass loss of the comet by a factor of two to 1.3 x 10^{10} kg/orbit. There is no more evidence of a periodic displacement with the epoch of ejection, which was though to be due to the precession of the comet spin-precession axis.

It is not clear to me, however, how to understand the position of the peak in Fig. 3, which implies an unreasonable 10 times higher mean density for the particles, if that peak position reflects the radiation pressure effect on spherical grains.

Table I lists the anticipated peak rates in 2002. Observations during the 2002 storm will help establish the nodal variation of the trail shifts with more certainty. In addition, precise measurements of the storm widths will discriminate between existing models. The most telling difference in this year's predictions concern the width of both storm peaks, which are three times broader in Lyytinen's model.

Table I. Dust distribution during past and future Leonid shower dust trail encounters.

Year	N	Epoch ejection	fm*	Δa* (AU)	Δr* (AU)	δr (AU)	W_{obs} (AU)	W_{cal} (AU)	ZHR_{obs} hr^{-1}	ZHR_{cal} hr^{-1}	λo_{obs} °)	λo_{cal} °)
2007	2	1932	0.56	1.060	-0.00040	(+0.00012)		0.00053		310		236.101
2006	2	1932	0.47	0.961	-0.00009	(+0.00012)		0.00043		680		236.609
2002	4	1866	0.15	0.172	-0.00005	(-0.00008)		0.00043		5400		236.878
2002	5	1833	0.12	0.120	+0.00148	(-0.00010)		0.00345		28		236.693
2002	6	1799	0.12	0.120	+0.00130	(-0.00003)		0.00295		51		236.645
2002	7	1767	0.13	0.113	-0.00015	(+0.00008)		0.00046		5900		236.601
2001	4	1866	0.13	0.142	+0.00022	+0.00014	0.0011(3)	0.00084	2,200(200)	2080	236.451(3)	236.450
2001	9	1699	0.43	0.041	+0.00015	+0.00016	-.-	0.00078	800(200)	790	~236.42	236.417
2001	6	1799	0.12	0.080	+0.00135	+0.00009	-.-	0.00372	<40	31	-.-	236.174
2001	7	1767	0.14	0.081	-0.00043	*+0.00082‡*	0.0014(2)	0.00087	1,300(200)	1,920	236.140(3)	*236.110*
2000	4	1866	0.13	0.114	+0.00077	+0.00012	0.0014(2)	0.00174	390(20)	340	236.259(3)	236.257
2000	8	1733	0.27	0.064	+0.00076	+0.00017	0.0025(6)	0.00185	230(20)	240	236.080(10)	236.084
2000	2	1932	0.55	0.300	-0.00120	+0.00017	0.0014(2)	0.00121	255(20)	245	235.275(3)	235.273
1999	4	1866	0.17	0.080	+0.0016	-0.00032	<0.0049(15)	0.00121	125(30)	26	235.91(4)	236.011
1999	5	1833	0.10	0.060	+0.0030	-0.00172	-.-	0.00185	~ 50	0	~236.0	236.085
1999	3	1899	0.38	0.138	-0.00066	+0.00022	0.00063(3)	0.00174	4,600(700)	3,700	235.285(2)	235.288
1998	3	1899	0.40	0.050	+0.00440	*-0.00608‡*	0.0024(7)	0.00296	70(30)	0	235.296(3)	*235.209*
1969	1	1932	0.95	0.934	-0.00004	-0.00010	0.00052(9)	0.00042	220(30)	230	235.274(3)	235.262
1966	2	1899	0.52	0.168	-0.00013	+0.00011	0.00049(5)	0.00049	15,000(3,000)	14,600	235.166(2)	235.149
1869	3	1767	0.44	0.320	-0.00047	-0.00023	-.-	0.00077	~1,000	3,660	~233.536	233.535
1867	1	1833	1.00	0.373	-0.00014	-0.00001	0.00042(7)	0.00051	4,500(900)	2,520	233.410(5)	233.411
1866	4	1733	0.37	0.059	-0.00029	+0.00014	0.00058(11)	0.00042	10,000(1,100)	10,500	233.327(4)	233.326
1833	1	1799	0.95	0.174	-0.00021	+0.00019	-.-	0.00051	~50,000	9,100	233.147(40)	233.176

*) Calculations from McNaught & Asher [7] and Lyytinen & Van Flandern [8-9].

‡) Displacement mostly due to perturbation by Earth in prior encounter

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4. REFERENCES

1. Wu Z., Williams I.P., *MNRAS* 280, 1210-1281, 1996.

2. Brown P.G.,Cook B., *MNRAS* 326, L19-L22, 2001.

3. Göckel C., and Jehn R., *MNRAS* 317, L1-L5, 2000.

4. Asher D.J., *MNRAS* 370, 919-924, 1999.

5. Mueller M., Green S.F., and McBride N., *ESA SP-495*, 47-54, 2001.

6. Kondrat'eva E.D., and Reznikov E.A., *Sol. Syst. Res.* 19, 96-101, 1985.

7. McNaught R.H., and Asher D.J., *WGN, the Journal of IMO* 27, 85-102, 1999.

8. Lyytinen E., 1999, *Meta Res. Bull.* 8, 33-40, 1999.

9. Lyytinen E.J., and van Flandern T., *Earth, Moon & Planets* 82-83, 149-166., 2000.

10. Yanagisawa T., Separation of 1699 yr and 1866 yr radiant points by use of the line detection method. *Presented at Leonid MAC Workshop*, May 2002.

11. Plavec M., *Publ. Astron. Inst. Cezchosl. Acad. Sci* 30, 1-94, 1957.

12. Jenniskens P., Crawford C., Butow S.J., Nugent D., Koop M., Holman D., Houston J., Jobse K., Kronk G., Beatty K., *Earth, Moon & Plan.* 82-83, 191-208, 2000.

13. Lyytinen E.J., Nissinen M., and van Flandern T., *WGN, the Journal of IMO* 29, 110-118, 2001.

14. Jenniskens P., *ESA SP-495*, 83-90, 2001.