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MASSIVE REMNANT OF EVOLVED COMETARY DUST TRAIL DETECTED IN THE ORBIT OF HALLEY-TYPE COMET 55P/TEMPEL-TUTTLE

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ABSTRACT

There is a subpopulation of Leonid meteoroid stream particles that appear to form a region of enhanced numbers density along the path of the stream. This structure has been detected in the vicinity of the parent comet, and its variation from one apparition to the next has been traced. A significant amount of known comet 55P/Tempel-Tuttle debris is in this component, called a "filament," which has dimensions exceeding by an order of magnitude that expected for a cometary dust trail. As filament particles are of a size comparable to those found in trails, the emission ages of the particles comprising the filament must be intermediate between the age of the current trail particles (which have not been observed) and the age of the background particles comprising the annual showers. The most likely explanation for this structure is planetary perturbations acting differently on the comet and large particles while at different mean anomalies relative to each other.

Subject headings: comets: individual (55P/Tempel-Tuttle) — dust, extinction — interplanetary medium — meteors, meteoroids

1. INTRODUCTION

Comet 55P/Tempel-Tuttle is in an unusual Halley-type orbit passing close to Earth's orbit every 33 odd years since 1000 yr ago. Historic accounts of meteor storms have mapped out a dust trail behind the comet and outside the comet orbit (Sekanina 1972; Yeomans 1981).

Here we report the detection of a dust filament that appears to be a later stage in the orbital evolution of these dust trails, containing as much mass as the annual shower debris. This new structure was traced out by unusual Leonid shower activity in the years preceding the 1998 February return of the comet and was again detected during the next passage of Earth by the stream in 1998 November. The unusual activity was recorded by forward meteor scatter techniques, each year adding a new cross section of the dust distribution in Earth's path. We also applied multistation photographic techniques for measuring the direction of motion of individual meteoroids at Earth and found the orbits to be dispersed and systematically displaced from year to year along the comet orbital plane. Planetary perturbations are implied as well as a relatively old age.

This filament is not a unique feature to the distribution of ejecta of comet 55P/Tempel-Tuttle. A similar structure was detected earlier in the orbit of Halley-type comet 109P/Swift-Tuttle, the only other Halley-type comet that comes close enough to Earth's orbit.

The presence of this older dust has important implications for understanding the orbital evolution of debris in the cometary dust trails that have been detected in the orbit of short-period comets by the thermal emission of the warm dust (Davies et al. 1984; Sykes et al. 1986; Sykes & Walker 1992).

2. OBSERVATIONS AND RESULTS

2.1. *Trail Cross Section and Particle Size Distribution*

After 25 yr of normal annual rates, unusual Leonid shower activity was first detected in 1994 (Jenniskens 1996). Ever since, Leonid outbursts have been recorded by visual observers and by automatic meteor counting stations using the technique of forward meteor scattering (Yrjölä & Jenniskens 1998). Here, as shown in Figure 1, we report on the counts of four Global-MS-Net stations in Finland (I. Yrjölä: *large filled circles*), Belgium (M. de Meyere: *open circles*), Ghent University, Belgium (Pierre de Groote: *open squares*), and the United States (Paul Sears: *small filled circles*). The meteor counts in excess of sporadic background rates are shown in Figure 1 as a function of time in terms of the Earth's position in its orbit (the solar longitude). The relative activity levels and the shape of the activity curves are in good agreement with the meteor counts by visual observers published elsewhere (e.g., Jenniskens 1995, 1996; Brown & Arlt 1997; Arlt 1998; Langbroek 1999). The time of the peak activity, the level of activity, and the duration of each return are summarized in Table 1.

The activity curves are usually well described by a profile of the generic shape (Jenniskens 1995):

$$\mathrm{ZHR} = \mathrm{ZHR}_{\max} \, 10^{|0.869(\lambda_\odot - \lambda_{\odot\,\max})/\Delta\Omega|} , \quad (1)$$

where ZHR is the zenith hourly rate that describes visual meteor counts by a standard observer under good observing conditions (star limiting magnitude = 6.5) and a radiant position in the zenith. A dashed line in Figure 1 is such a profile for an assumed nodal dispersion of $\Delta\Omega = 0\overset{\circ}{.}8$. The near-constant width at positions in the dust trail that are passed by Earth years apart implies a trail, ribbon, or filament-like structure. In this paper, we will refer to this structure as the "Leonid filament."

The nodal dispersion defines the thickness of this filament, taking into account that the Leonid shower cuts the Earth's orbit at a shallow angle of $18\overset{\circ}{.}1$ (Kresák & Porubcan 1970). The FWHM perpendicular to the comet orbit is FWHM = 6×10^5 km. The annual shower debris in comparison has a 6 times higher FWHM = 3.5×10^6 km (Jenniskens 1996).

A similar broad dust component was observed during the previous 1965 encounter, and was observed first in 1961 (Jenniskens 1996). At that time, too, it was rich in bright meteors and occurred when the Earth was outside the comet orbit and in front of the comet. If we assume that

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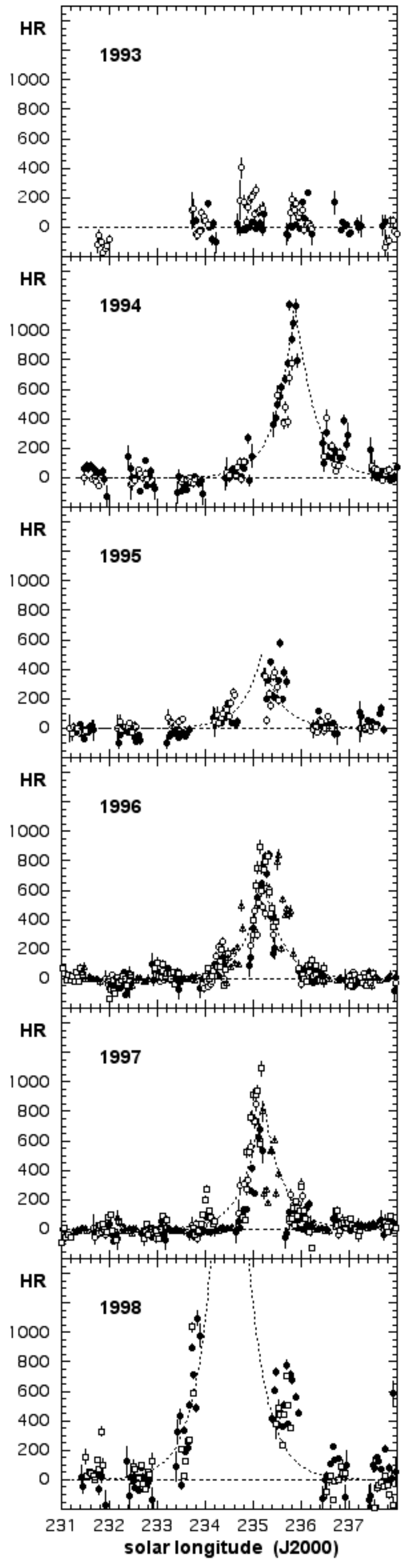

FIG. 1.—Leonid meteor hourly rates (HR) from forward meteor-scattering experiments.

both accounts describe the same debris, then the difference in minimum distance between the comet and Earth's orbit in 1994 and 1961 (0.0033 vs. 0.0080 AU) sets a lower limit to the dispersion perpendicular to the Earth's orbit: greater than 7×10^5 km. This value is of the same order as the measured thickness.

The filament appears to be confined to the vicinity of the comet. There is no sign of this dust component during "off-season" years in the compilations of Leonid meteor shower observations from the period 1981–1991 (Jenniskens 1996; Koseki 1993; Brown 1994). Hence, the 1994 and 1961 returns represent a sudden onset. The component extends from this onset until at least 1 yr after passage of the comet because of strong returns observed in 1965 and recently in 1998. Less certain observations exist for the period 1966–1968 (Table 1). If we assume that the debris can be detected for a period of 8 yr around the passage of the comet, then it is dispersed only over about $\frac{1}{5}$ of the comet orbit. In contrast, the annual shower debris is evenly distributed along the comet orbit with no strong enhancement near the vicinity of the comet (Jenniskens 1996).

Peak rates gradually increase until a peak just behind the comet and gradually decrease after that (Fig. 2). From this general trend, the activity in 1994 and 1961 stands out as being unusually intense. The similar behavior of the returns is striking. Note also that the time of the peak relative to the comet node follows the behavior of the 1965 return, with the exception of 1994 (Fig. 2). Comet 55P/Tempel-Tuttle had an ascending node at 235°.12 in 1965 and at 235°.26 in 1998 (J2000).

In all those years, the showers were relatively abundant in bright meteors with corrected rates increasing by only a factor of $\chi = N(m+1)/N(m) = 1.4–2.3$ per magnitude interval, the population index. In comparison, $\chi = 3.0 \pm 0.2$ during past Leonid storms (Jenniskens 1995). Correspond-

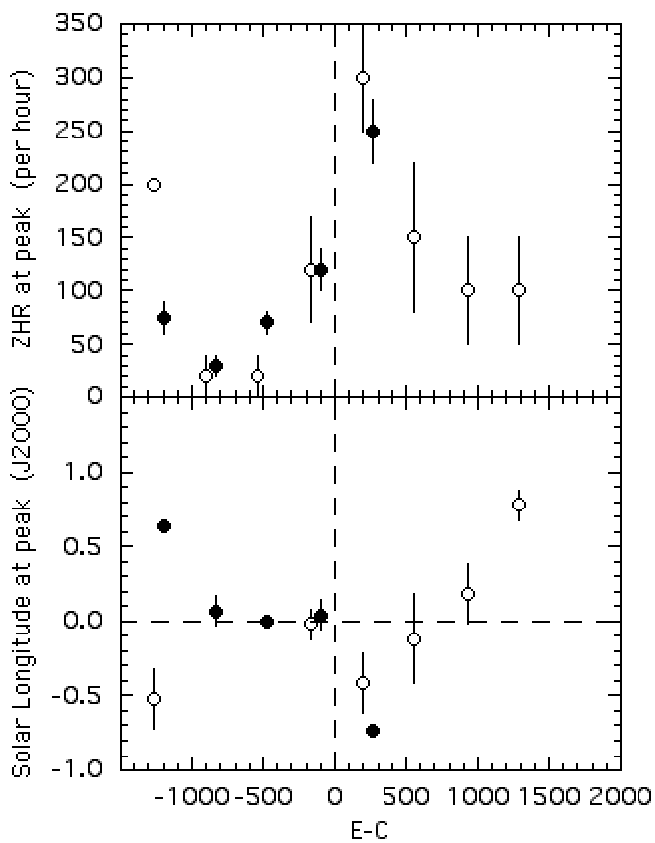

FIG. 2.—Peak activity and time of maximum of Leonid filament outbursts during 1961–1968 and 1994–1998.

TABLE 1

SUMMARY OF RATE PROFILES AND PARTICLE SIZE DISTRIBUTIONS FOR LEONID FILAMENT RETURNS

				1965 RETURN			1998 RETURN		
YEAR	E–C[a] (days)	FWHM (deg)	x	Peak $\lambda_{\odot}$ (J2000) (deg)	ZHR_{max} (hr^{-1})	ρ_{max}[b] (10^{-24} g cm^{-3})	Peak $\lambda_{\odot}$ J2000 (deg)	ZHR_{max} (hr^{-1})	ρ_{max}[b] (10^{-24} g cm^{-3})
1981–1991	...	...	...				...	<3	<0.3
1960	−1630	...	...	...	<10	<1			
1993	−1358	...	...	...	<10	<1			
1961	−1265	...	2.3	234.6 ± 0.2	~200	~5			
1994	−993	0.8 ± 0.1	2.1 ± 0.3				235.90 ± 0.04	75 ± 15	3.2
1962	−900	...	...	...	<40	<2			
1995	−628	~0.8	2.0 ± 0.3				235.33 ± 0.10	30 ± 10	1.7
1963	−535	...	...	...	~20	~1.1			
1996	−262	0.7 ± 0.2	1.9 ± 0.9				235.26 ± 0.04	70 ± 10	5.3
1964	−170	...	...	235.1 ± 0.1	~120	~11			
1997	−103	0.6 ± 0.1	...				235.3 ± 0.1	120 ± 20	9.1
1965	+196	~0.8	~1.7	234.7 ± 0.2	~300	40			
1998	+262	0.8 ± 0.1	1.5 ± 0.1				234.52 ± 0.01	250 ± 20	37.8
1966	+561	...	...	235.0 ± 0.3	<150	<10			
1967	+926	...	...	235.3 ± 0.2	~100	~8			
1968	+1291	...	...	235.9 ± 0.1	~100	~8			
1969	+1656	...	...	...	<10	<1			
1970	+2021	...	...	...	<10	<1			

NOTE.—Sources: Jenniskens 1996; Langbroek 1996, 1999; Brown & Arlt 1997; Arlt 1998.

[a] Earth-comet difference in time of model passage.

[b] ρ is mass influx for meteoroids with $V < 6.5$.

ing values for the differential mass distribution index are $s \sim 1.6$ and $s = 2.19$, respectively. There is some indication that the largest particles are found dominantly near the position of the comet, with $\chi = 1.5 \pm 0.1$ in 1965 and 1998, behind the position of the comet at the peak of the filament dust density.

From all this, we calculated a total mass of about 1×10^{15} g for particles between 10^{-6} and 10^{2} g (-5 to 7 mag Leonids), following the procedure in Jenniskens (1994). This mass is dominated by large grains. (The mass range is chosen to be the same as that in Jenniskens 1994, 1995 for reasons of comparison. The total mass is 5×10^{-15} g if we include Leonids as bright as magnitude -14, or 10^{3} g, which are the brightest Leonids observed during the 1998 outburst.)

This is close to half of the total mass in the annual shower debris (2×10^{15} g) and significantly more than the 2×10^{13} g of the dust trail responsible for past Leonid storms, which we estimate from the peak intensity, duration, and spatial distribution reported in historic accounts (Jenniskens 1995). The latter mass estimates are in fact higher than our previous values because we incorrectly used an algorithm that broke down for entry velocities close to 72 km s^{-1} (with little or no consequences for other showers, hence the error remained unnoticed).

The new mass estimates reported here compare to 10^{11}–$10^{14.5}$ g for the mass estimates of cometary dust trails of short-period comets by Sykes & Walker (1992). The dimensions of the Leonid filament (6×10^{5}, $>7 \times 10^{5}$ km) are comparable to the widths of the Encke (6.8×10^{5} km) and Schwassmann-Wachmann 1 (7.7×10^{5} km) dust trails, but they are about a factor of 10 larger than other trail widths.

2.2. *Individual Meteoroid Orbits*

During the Leonid return of 1995, 1997, and 1998, we successfully obtained trajectories and orbits of individual meteoroids at the time of the Leonid outbursts. In order to do so, we deployed multistation networks of batteries of small 35 mm format cameras. The method is described in Betlem et al. (1998). Results from the 1995 and 1998 campaigns are presented in Betlem et al. (1997, 1999). In Table 2, we present the trajectory and orbits of 10 Leonids from the 1997 campaign, which was conducted in California with support from members of the California Meteor Society.

From the relative intensity of annual and outburst components of shower activity, we conclude that a significant fraction of the observed meteors are expected to be part of the outburst component, some 60% of the 1995 Leonids and close to 100% of those photographed in 1997–1998.

All radiant positions are plotted in Figure 3 after correction for the daily changing direction of motion of Earth itself to that at solar longitude $\lambda_{\odot} = 235.^{\circ}0$, i.e., ΔR.A. $= +0.^{\circ}99$, Δdecl. $= -0.^{\circ}36$ per degree solar longitude. The 1997 data are of lower accuracy because of a full Moon, which results in the detection of only that part of the meteor trail that is bright (and often overexposed). On the other hand, the 1997 data form an interesting sequence in combination with the 1995 and 1998 results.

Only seven of the 29 radiants measured in 1995 form a dense cluster at R.A.(J2000) $= 153.^{\circ}63 \pm 0.^{\circ}11$, decl.(J2000) $= +21.^{\circ}97 \pm 0.^{\circ}03$. All radiants measured in 1997 are located close to that position, but slightly displaced and centered at R.A. $= 153.^{\circ}77 \pm 0.^{\circ}11$, decl. $= +22.^{\circ}03 \pm 0.^{\circ}06$ (Fig. 3). Those of 1998 are displaced from that again, now centered at R.A. $= 153.^{\circ}80 \pm 0.^{\circ}08$, decl. $= +22.^{\circ}10 \pm 0.^{\circ}03$.

In all years, the radiant distribution is significantly dispersed. Without good criteria to distinguish between cluster

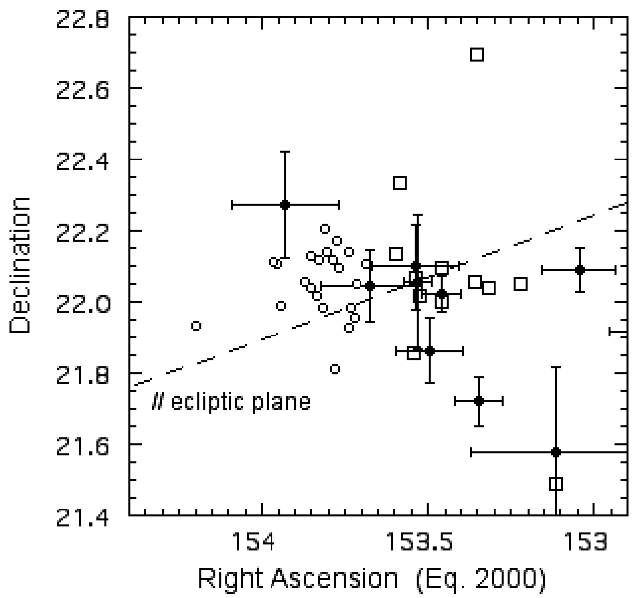

FIG. 3.—Radiant distribution of Leonid meteors in 1995 (*open squares*; Betlem et al. 1997), 1997 (*filled dots*; this paper), and 1998 (*open dots*; Betlem et al. 1999).

TABLE 2

OSCULATING ORBITAL ELEMENTS OF 1997 OUTBURST LEONIDS AT THE EPOCH OF THE METEOR

Time (1997 Nov 17)	R.A.[a] (deg)	Decl.[a] (deg)	V (km s^{-1})	Hb (km)	He (km)	mv (mag)	M/C$_D$S (g cm^{-2})	1/a (AU^{-1})	q (AU)	i[a] (deg)	ω[a] (deg)	Ω[a] (deg)
9:22:23	153.63 ± 0.04	+21.82 ± 0.19	71.9 ± 0.4	114.1	91.6	−1	0.14	+0.08 ± 0.04	0.9843	162.06	171.72	235.0987
10:02:01	152.91 ± 0.17	+21.87 ± 0.16	71.8 ± 0.5	113.0	96.6	−1	0.04	+0.10 ± 0.04	0.9863	162.71	174.32	235.1264
10:56:58	153.70 ± 0.13	+22.04 ± 0.12	71.6 ± 0.7	109.3	97.4	0	0.18	+0.10 ± 0.07	0.9843	161.96	172.18	235.1649
10:50:30	154.13 ± 0.16	+22.20 ± 0.15	70.1 ± 1.0	106.0	81.6	−4	...	+0.23 ± 0.09	0.9825	161.16	170.31	235.2024
11:54:46	153.70 ± 0.10	+21.79 ± 0.09	71.4 ± 0.4	115.9	91.6	−2	...	+0.12 ± 0.04	0.9840	162.32	171.90	235.2054
12:00:33	153.32 ± 0.26	+21.50 ± 0.24	71.9 ± 0.7	117.2	92.9	−3	0.01	+0.08 ± 0.07	0.9850	163.10	172.92	235.2094
12:11:55	153.26 ± 0.11	+22.01 ± 0.06	71.1 ± 0.4	112.2	84.5	−10	0.09	+0.15 ± 0.04	0.9857	162.19	173.53	235.2174
12:25:24	153.57 ± 0.07	+21.64 ± 0.07	71.0 ± 0.5	114.4	94.1	−1	0.18	+0.16 ± 0.04	0.9841	162.57	171.96	235.2268
12:45:54	153.91 ± 0.15	+21.96 ± 0.10	72.3 ± 1.5	114.6	86.5	−2	0.006	+0.02 ± 0.14	0.9840	162.11	172.10	235.2412
13:03:05	153.71 ± 0.06	+21.93 ± 0.05	71.4 ± 0.7	112.1	89.4	−2	0.02	+0.11 ± 0.07	0.9843	162.12	172.26	235.2532

[a] Geocentric radiant, equinox J2000.

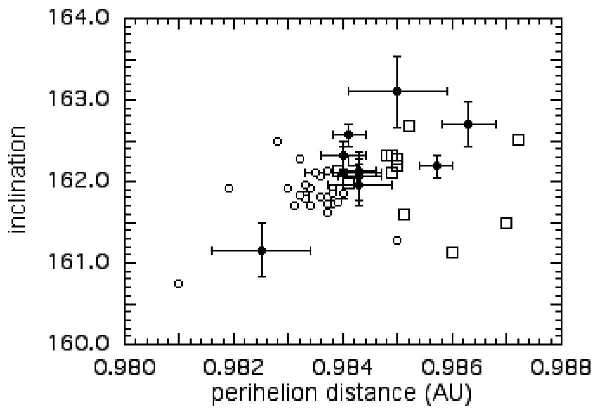

FIG. 4.—Distribution of orbital elements (symbols as in Fig. 3)

and noncluster 1995 Leonids and because of relatively large errors in the 1997 data, it is not possible to state that the dispersion measured in 1995 is significantly different from that measured in 1997 or 1998.

From the radiant and mean speed along the trajectory, the orbital elements are calculated (Table 2). The semimajor axis is clustered near that of the comet, as expected if ejection velocities are low. The observed dispersion in radiant positions translates into a significant dispersion in the orbital elements. The systematic yearly shift in radiant position returns in the graph of perihelion distance versus inclination, for example, as a gradual shift in both q and I from year to year (Fig. 4).

3. DISCUSSION

3.1. *A New Structure*

The photographed meteors probe particles of mass about 0.3 g, or a diameter of order 1 cm, using the general formula for the mass of a given meteor brightness by Jacchia, Verniani, & Briggs (1967). Meteoroids of that size are typically associated with cometary dust trails rather than tails (Sykes & Walker 1992). Kresák (1993) first argued a generic link between cometary dust trails and meteor storms.

Our initial interpretation of the meteor data was that of Earth crossing a classic dust trail (Jenniskens 1995; Jenniskens et al. 1997). We assumed that the relatively low peak activity in years before passage of the comet by perihelion might occur on account of an asymmetry that is common in dust trails. Dust trails tend to be more extended behind the comet (Sykes & Walker 1992). This asymmetry is generally understood as a result of the effect of ejection velocities causing asymmetric distributions in semimajor axis (Plavec 1955) and the effect of radiation forces that effectively lower the radial force from the Sun's gravity, putting the particles in wider orbits (Kresák 1976). After one return, the grains tend to lag the comet, an effect that is most severe for the smallest grains. One would expect a gradually increasing population index along the dust trail.

We now find that the population index increases rather than decreases when approaching the comet position and is always significantly less than observed during the Leonid storms of 1966 and 1866–1867 (Table 2).

It was observed earlier (Jenniskens 1996; Brown, Simek, & Jones 1997) that multiple dust components are recognized in the available radar observations of the 1965 return (McIntosh & Millman 1970), the filament being distinct from other less-dispersed structures (Fig. 5). This was seen again during the return of 1998 (Jenniskens 1999). The similar population index and duration of the outbursts in the years 1994–1998 give further support to the hypothesis that the 1961 and 1965 outbursts were caused by the same dust feature (the filament).

That planetary perturbations of the meteoroid orbits are important follows from the relatively large dispersion of the radiants and the node. The observed thickness of the filament and the radiant dispersion are consistent with ejection velocities of order 90 m s^{-1}. This is a factor of 3 higher than the $V_{ej} \sim 30$ m s^{-1} calculated from the classical theory of ejection by water vapor drag assuming a nominal density of 1 g cm^{-3}, ejection at perihelion, and 0.1 g particle (Whipple 1951; Jones & Brown 1997). Note that the much smaller nodal dispersion of meteor storms implies lower ejection velocities $V_{ej} \sim 5$ m s^{-1}. One possible explanation is that the filament grains may have had an episode of better gas-to-dust coupling by ejection from depressed active areas (Jones 1995; Jones & Brown 1997), by being flake- or needle-shaped (Gustafson 1989) or perhaps because they are accelerated by ice grain ejection (Steel 1994). However, such a high ejection velocity would imply rapid dispersion along the comet orbit. A single revolution would be sufficient to spread the dust as many years before and behind the comet position as observed. And subsequent revolutions would increase that dispersion. That leaves only the possibility that the dispersion is a signature of planetary perturbations and a sign of relatively high age.

As filament particles are of a size comparable to those found in trails, the emission ages of the particles comprising the filament must be intermediate between the age of the current trail particles (which have not been observed) and the age of the background particles that comprise the annual showers (Fig. 5).

3.2. *Evolved Dust Trails*

Recently, Asher, Bailey, & Emelyanenko (1999) argued that the filament is caused by ejection of dust grains into the 5/14 mean motion resonance with Jupiter, principally during the perihelion passage of comet 55P/Tempel-Tuttle in 1333. This trapping in resonances has the effect that particles do not spread uniformly around the orbit, but instead librate about a resonance center within the main stream. The particles remain concentrated in space, but differential precession between the comet orbit and the orbits of these resonant particles can lead to increasing differences in the orbital elements over time.

Our observations lend support to such a scenario, but also support the alternative scenario proposed by Jenniskens et al. (1998) that the grains were ejected with small ejection velocities and were protected from close encounters with the planets by virtue of the comet librating around an orbital resonance.

Librations around mean motion resonances tend to stabilize the comet orbit for some time and protect the region near the comet for close encounters with the planets. Rather than being near the 2:5 orbital resonance with Uranus (Williams 1997), the comet's semimajor axis is currently oscillating around the 5:14 resonance with Jupiter and the 8:9 resonance with Saturn. Librations around higher order resonances are a common phenomenon. The comet itself

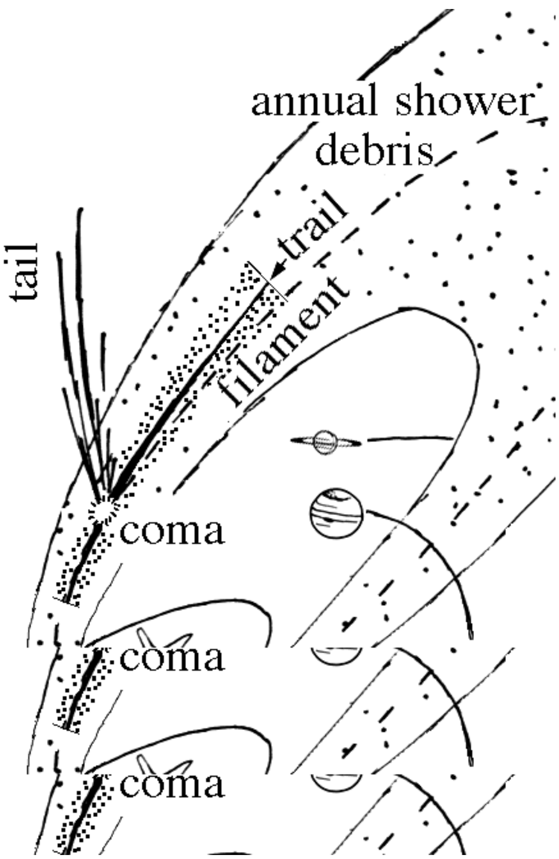

FIG. 5.—Cartoon showing the new filament structure in relation to other known cometary dust features.

shows the most severe perturbations during relatively close (<1 AU) encounters with Jupiter and Saturn. Close encounters over the 2000 yr interval studied by Yeomans, Yau, & Weissman (1996) tended to cluster near 0.55 or 0.85 AU rather than values in between, although both planets do approach the comet orbit closer than that. The region nearest to the comet has been free from close encounters for some time. In this scenario, the part of the orbit encountered in 1994 and 1961 has been less perturbed than the part encountered prior to 1994 and even the part encountered around 1995 (Fig. 5).

It is the larger grains especially that can survive in this region: the smaller grains are ejected with higher ejection velocities and tend to spread over time toward parts of the orbit that are prone to close encounters. This may account for the less steep size distribution and subsequent relative abundance of bright meteors.

This interpretation suggests that the Leonid filament represents an accumulation of matter over several apparitions. The dust filament can continue to build up until the end of a libration cycle and a transition to another orbital resonance. From the relative mass content of the dust trail and filament, that accumulation of matter must have occurred over at least 10–100 perihelion returns, which puts the age of the filament at about 10^3 yr. This is equivalent to the timescale over which Halley-type comet 109P/Swift-Tuttle tends to librate around a mean-motion resonance: 5×10^3 yr (Chambers 1997).

The conclusion that matter accumulates over several apparitions is bolstered by the large mass present in the filament. Unless the matter is distributed in a thin sheet, rather than the more or less cylindrical structure suggested by the similarity of the 1998 and 1965 returns, the total mass calculated for the filament (1×10^{15} g) is much larger than the typical ejecta of a single perihelion return. The large-grain dust mass loss per apparition estimated for the *IRAS* trails of short-period comets (calculate from Sykes & Walker 1992) is 8.0×10^{11} g for Churyumov-Gerasimenko, 2.8×10^{13} g for Encke, 4.0×10^{12} g for Gunn, 1.7×10^{12} g for Kopff, 9.4×10^{11} g for Pons-Winnecke, 4.2×10^{13} g for Schwassmann-Wachmann 1, 1.6×10^{12} g for Tempel 1, and 3.0×10^{12} g for Tempel 2 (M. V. Sykes 1999, private communication). These estimates represent minimum mass-loss rates and assume that all trail particles have a maximum beta of 10^{-3} (if one assumes a trail particle mass density of 1 g cm^{-3}, then the mass of this particle is $\sim 10^{-3}$ g).

Hence, our interpretation of the observations argues against the hypothesis of Asher et al. (1999) that ejection of a single perihelion return, that of 1333, is responsible for the observed shower, unless that return was unusually (10–100 times more) active. Rather, there has been an accumulation of dust in the past 1000 yr. It is the recent orbital evolution of the comet that resulted in this temporary accumulation of debris, rather than the entrapment of meteoroids in orbital resonances. Interestingly, however, it is possible that the libration of meteoroid orbits around mean motion resonances plays a role in the orbital evolution of this filament.

3.3. *Filaments as a Generic Feature of Halley-Type Comets*

One other Halley-type comet comes close enough to Earth's orbit to cause meteor outbursts if a similar filament structure is present. Indeed, centered on the return to perihelion of 109P/Swift-Tuttle, a series of meteor outbursts were observed that traced a similar meteoroid debris component, called the Perseid filament (Brown & Rendtel 1996; Jenniskens et al. 1998).

Here we point out the similarities between the Perseid and the Leonid "filaments" (Table 3). Common features are the low and similar population index x, the amount of time that the matter is detected in front of and behind the comet, and the total amount of mass in the structure (assuming its dispersion perpendicular to the Earth's path is as large as that of the Leonid filament).

Moreover, there is a remarkable similarity in the radiant structure. In our analysis of the Perseid shower, we discovered the same dynamic pattern as found in this paper: the radiants are dispersed in individual years and the mean radiant position in each year is significantly displaced from one year to the other along a line at an angle to the ecliptic plane (Jenniskens et al. 1998).

The thickness of the Perseid filament is a factor of 4 less than that of the Leonid filament. Perhaps this reflects the fact that 109P/Swift-Tuttle is in a 1:11 mean motion resonance with Jupiter rather than librating around a higher order resonance. Coincidentally, the orbital period of 109P/Swift-Tuttle is 4 times larger than that of 55P/Tempel-Tuttle.

Filaments may be a common feature of the orbital evolution of cometary debris of Halley-type comets and perhaps also of other type comets. Much of the mass loss of these comets is accumulated in this massive remnant. Hence, this is a significant phase in the orbital evolution of large cometary dust grains.

TABLE 3

COMPARISON OF LEONID AND PERSEID FILAMENTS

Parameter	Leonid Filament	Perseid Filament
Size distribution index (s)......	1.6 ± 0.2	1.7 ± 0.1
Width (km)......................	6×10^5	1.4×10^5
In-plane dispersion (km).......	$>7 \times 10^5$	$>6 \times 10^5$
Length (yr)......................	8	8
Peak flux (g cm^{-3})	4×10^{-23}	7×10^{-23}
Mass (g)	1×10^{15}	5×10^{14}

Although 109P/Swift-Tuttle is many years past the previous perihelion passage, 55P/Tempel-Tuttle's filament may still be observed. Observations from the 1966–1969 period are not abundant (Table 1) but do suggest that the Leonid filament continues to be visible at least until 2002.

We thank all amateur observers who participated in the 1997 Leonid campaign in California: at station Goldstone: Mike Koop, Lance Brenner, Bob Lunsford, Sandra Macika, and Peter Zerubin; at station Walker-Pass: Chris Angelos, Ming Li, Duncan McNeill, and Jim Riggs; and at station Edwards Air Force Base: Hans Betlem. Peter Brown provided travel support for Hans Betlem. Global-MS-Net observers I. Yrjölä, M. DeMeyere, P. de Groote, W. Kuneth, and P. Sears contributed the forward meteor scatter observations. The paper benefited greatly from discussions with Mark Sykes. This work was accomplished with support of NASA's Planetary Astronomy program.

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