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# Resonant meteoroids from Comet Tempel–Tuttle in 1333: the cause of the unexpected Leonid outburst in 1998

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## ABSTRACT

Recent observations of an unexpectedly high incidence of bright Leonid meteors about 16 h before the predicted maximum of the main shower are explained by the 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. The dynamical evolution of resonant grains has the following properties: first, the grains do not spread uniformly around the orbit, but instead librate about a resonance centre within the main stream; secondly, these resonant zones contain a much higher space density of particles than the background stream, with the particle density approaching that of recently ejected cometary grains; thirdly, differential precession between the cometary orbit and the orbits of resonant particles may lead to meteor storms at unexpected times, possibly far removed from that of the normal shower. The presence of resonant dust grains leads to a complex structure within the Leonid meteoroid stream, and is an important general feature of meteoroid streams associated with Halley-type comets, themselves often trapped for long periods in mean-motion resonances.

**Key words:** comets: individual: 55P/Tempel–Tuttle – meteors, meteoroids – Solar system: general.

## 1 INTRODUCTION

The annual Leonid meteor shower occurs between approximately November 15 and 21 each year, with a maximum during November 17/18. It is historically one of the best known meteor showers, with records of meteor storms (visual meteor rates greater than $10^3$ per hour) extending back more than a thousand years to AD 899 (Astapovich 1968; Katasev & Kulikova 1972; Yeomans 1981; Yeomans, Yau & Weissman 1996). These episodes of very high meteor flux usually occur within a few years of the perihelion passage of the parent comet. Since Comet 55P/Tempel–Tuttle passed perihelion on 1998 February 28, there was much interest in the shower of 1998 and its implications for 1999 and 2000.

In the event, although predictions of the strength of the 1998 event (Brown & Jones 1996; Jenniskens 1996; Wu & Williams 1996,Yeomans et al., 1996; Arlt, Molau & Currie 1998) were broadly vindicated, indicating a strong shower but no storm, astronomers and other commentators were surprised by a strong peak in the fireball flux more than half a day earlier than expected. Whereas the normal maximum of the meteor storm component occurs close to solar longitude (equinox J2000.0) $\lambda_\odot = 235\overset{\circ}{.}25$ (1998 November 17.8), compared with the peak of the background non-storm meteor shower at $\lambda_\odot \simeq 235\overset{\circ}{.}5$ (Brown 1994), corresponding to 1998 November 18.0, the observed fireball flux peaked much earlier at $\lambda_\odot = 234\overset{\circ}{.}5$ (1998 November 17.1).

The observed fireball outburst was distinguished by an exceptionally low population index (Arlt 1998), i.e. by a predominance of very bright meteors originating from large dust grains with sizes ranging up to a few centimetres. The highest level of fireball activity lasted approximately half a day, indicating the presence of a narrow, concentrated substream containing relatively large particles. The different particle size distribution together with the surprising difference in time from the predicted shower maximum suggests that the outburst was produced by a distinct population of large grains moving in a different orbit from that of the parent comet.

## 2 RESONANT MOTION

A substantial number of short-period comets exhibit resonant motion (Marsden 1970; Franklin et al. 1975; Emel'yanenko 1987; Carusi & Valsecchi 1987). The importance of resonances has been demonstrated in the long-term dynamical evolution of both Encke-type orbits (Asher & Clube 1993; Farinella et al. 1994; Valsecchi et al. 1995) and Halley-type comets (Asher et al. 1994; Bailey & Emel'yanenko 1996). Indeed, recent work (e.g. Bailey 1996) has emphasized some surprising similarities in the long-term orbital evolution of these otherwise rather different classes of orbit. As far as the Leonids are concerned, Comet 55P/Tempel–Tuttle is well

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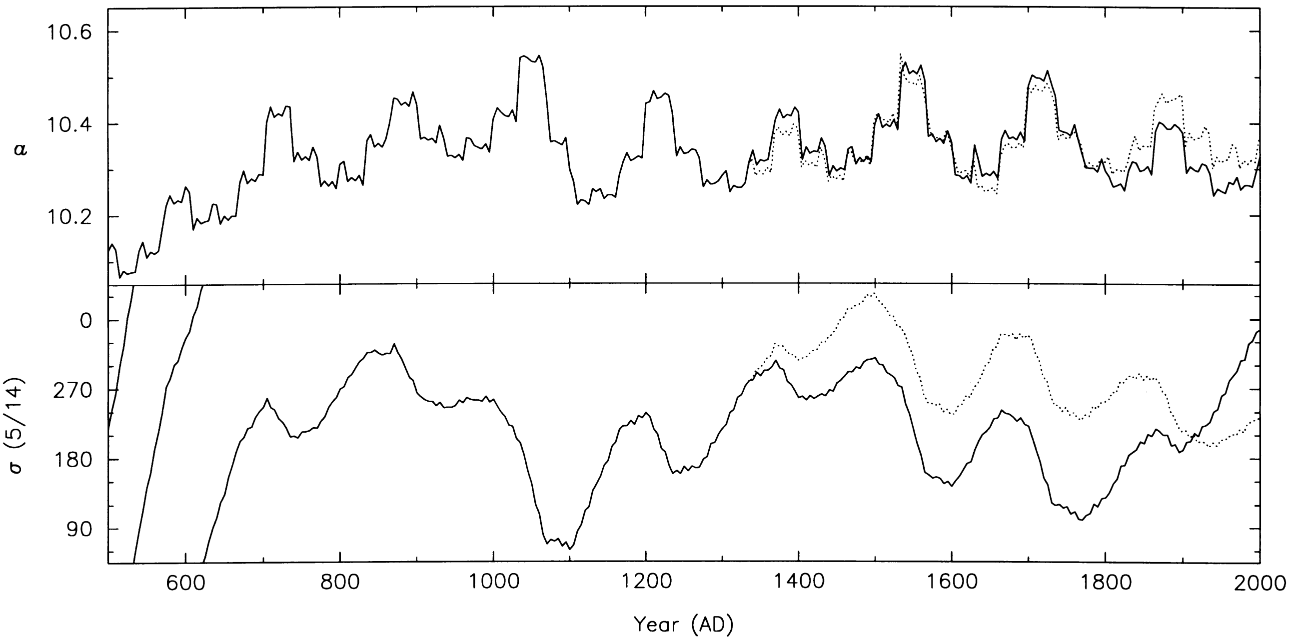

**Figure 1.** Evolution in semimajor axis $a$ of 55P/Tempel–Tuttle for 1500 yr (solid line), together with that of a typical particle ejected in 1333 (dotted line) that intersects the Earth at 1998 November 17.1. The critical argument, $\sigma$, plotted for the 5/14 mean-motion resonance with Jupiter, is a measure of the location of the particle with respect to the resonance centre. The comet appears to have entered the resonance during the seventh century, indicated by the transition of $\sigma$ from circulating to librating values.

known to be in the 5/14 mean-motion resonance with Jupiter (Stoney & Downing 1899). We therefore considered the possibility that dust particles released from the comet at a previous perihelion passage might be trapped in the same resonance, leading to a high particle concentration in space and also to a sufficiently different orbit to explain the observed meteor outburst.

If a Leonid particle lies in the $j/j' = 5/14$ mean-motion resonance with Jupiter, it will have a mean semimajor axis $\bar{a} \simeq 10.35$ au (Emel'yanenko 1988). Jovian perturbations constrain the semimajor axis $a$ of the particle to vary periodically, with corresponding variations in the critical argument $\sigma = j'M - j(M_J + \omega_J + \Omega_J - \omega - \Omega)$, where $M$, $\omega$ and $\Omega$ are the mean anomaly, argument of perihelion and longitude of ascending node respectively, the suffix J denoting Jupiter. The motion is analogous to that of a simple pendulum, the period and amplitude depending on the distance of the particle from the resonance centre, $\bar{\sigma}$. Fig. 1 shows the evolution of $(a, \sigma)$ for 55P/Tempel–Tuttle for approximately the last 1500 yr.

The large dust grains ejected from the comet are predominantly ejected into the same 5/14 resonance as the comet, and cannot spread around the orbit in the usual way. (Other resonances, such as the 1/3 and 4/11, may also be populated, but these did not contribute to the outburst in 1998.) Instead, they produce a long-lived, high-density concentration of particles, taking the form of an arc of material located close to, but not necessarily identical with, the parent cometary orbit. The 'regular' motion of librating particles within the resonance contrasts with the more chaotic motion of non-resonant grains, and allows the local particle density to build up to a level comparable to that of the non-resonant, recently ejected particles. These features of resonant meteoroid streams have been investigated previously, both numerically and analytically (Emel'yanenko 1984, 1988). Resonant particles, despite their age, may produce very concentrated meteoroid streams (Emel'yanenko & Bailey 1996), which although potentially dangerous are fortunately predictable. Indeed, with the benefit of hindsight, the a priori probability of a fireball outburst was higher in 1998 because the Earth passed close to the centre of the resonant zone occupied by 55P/Tempel–Tuttle and much of its debris.

Resonances have similarly been proposed as relating to meteor displays and meteoroid bombardment from other streams, such as the Lyrids (Emel'yanenko 1991), Taurids (Asher & Clube 1993; Asher & Izumi 1998) and Perseids (Jenniskens et al. 1998). The orbit of the Lyrid parent comet is rather uncertain, but the effects of a resonance are suggested by the detailed variation of the meteor shower from year to year and the location of the showers with respect to the predicted centre of the resonance. For the 1998 Leonids, however, the well-known cometary orbit together with the regular rather than stochastic nature of the resonant orbits allows us to prove the resonant motion by identifying the particular time when the particles were ejected.

For this purpose we used the Radau integrator (Everhart 1985), two orbits for the comet (Nakano 1997, 1998), and initial planetary elements (Mercury to Neptune) taken from the Jet Propulsion Laboratory (JPL) ephemeris DE403. The orbits were based on observational arcs respectively from 1366 to 1997 and from 1866 to 1998, the fact that the results were derivable with either representing a useful consistency check. The comet was integrated backwards in time using the MERCURY integrator package (Chambers & Migliorini 1997), including its non-gravitational acceleration, to find its orbit at each previous perihelion. This indicated that it has been resonant since the seventh century (Fig. 1). Beginning at each of the past 42 perihelion passages, 40 particles were integrated forward to 1998 November 17.1, checking also the possible contributions to the Leonid shower at other dates including 1965, 1966, 1999 and 2000. These particles were assumed to be ejected at perihelion, varying only the semimajor axis $a$ since that is what dominates the subsequent evolution. The value of $a$ was initially chosen to be within 0.2 au of the comet, with particles spaced equally by 0.01 au. The integrations starting more than a few

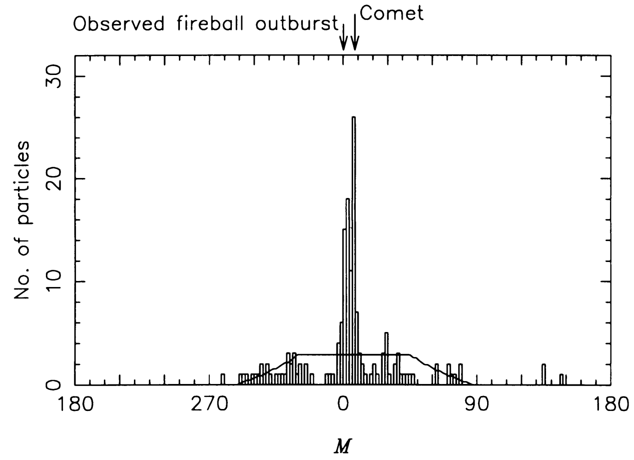

**Figure 2.** Distribution in mean anomaly $M$ at 1998 November 17.1 of particles ejected at low velocities (corresponding to an initial displacement $|\Delta a| < 0.05$ au from the semimajor axis of the comet) at successive perihelion passages from 1001 to 1499. This shows the strong concentration of 5/14 resonant particles mainly within a range of ~10°. If the orbital periods of the particles had remained at their initial values (i.e. if there were no resonance), the range of $M$ would be much wider, as shown schematically by the solid line.

centuries ago showed that particles were injected into the resonance, and usually remained in it until the present time, although only over a relatively small range ~0.05 au of the initial semimajor axis. (Occasionally, when the comet was itself near the centre of the resonance, this range extended to more than 0.1 au.)

The amplitudes of oscillation about the resonance centre vary among the different particles, but the overall effect is that they concentrate mainly over a range of ~10° in mean anomaly $M$ (Fig. 2). If, for each ejection epoch, the spread in $M$ were to increase linearly with time (which it would if all orbital periods remained constant, and which it does for the first century or so), the range in $M$ in Fig. 2 would be of order 90°. At present, the comet is located near the leading edge of the resonant concentration, while the Earth passed through the concentration a little behind the centre in 1998 November.

We next explored the spatial structure of this resonant substream with regard to identifying the particles that produced the observed fireball outburst. In order for particles ejected at a particular previous perihelion passage to collide with the Earth in 1998 during their descending nodal passage at heliocentric distance $r_{\mathrm{D}}$, it is necessary that they (i) cross the ecliptic at the same heliocentric distance as the Earth; (ii) have orbits such that the longitude $\Omega$ of their ascending node corresponds exactly to the time of the outburst; and (iii) have mean anomalies such that they cross the descending node at the time of the outburst (1998 November 17.1).

For a century or two, the range in mean anomaly $M$ of particles ejected at a given time tends to spread out as a reasonably smooth function of the orbital period at ejection, equivalently the initial semimajor axis $a_0$. Thereafter, $M$ as a function of $a_0$ becomes increasingly fragmented over the range ±0.2 au in $a_0$ being considered, but our chosen resolution of 0.01 au in $a_0$ nevertheless allows most ranges in $a_0$, at most perihelion passages, to be excluded as possible sources of meteors in 1998, i.e. condition (iii) is certainly not satisfied. As regards condition (i), $r_{\mathrm{D}}$ (in 1998) varies as a function of $a_0$ through planetary perturbations, but, as with (iii), there is sufficient pattern in $r_{\mathrm{D}}$ for most ranges of $a_0$ to be excluded. Here we required $r_{\mathrm{D}}$ to be within a few times 0.0001 au of the Earth's value, permitting such dispersion on account of variations in orbital elements other than $a$ that may occur on ejection (cf. Asher 1999). For resonant particles, the further dispersion in $r_{\mathrm{D}}$ over several centuries is significantly limited by the effects of the resonance (Emel'yanenko & Bailey 1996).

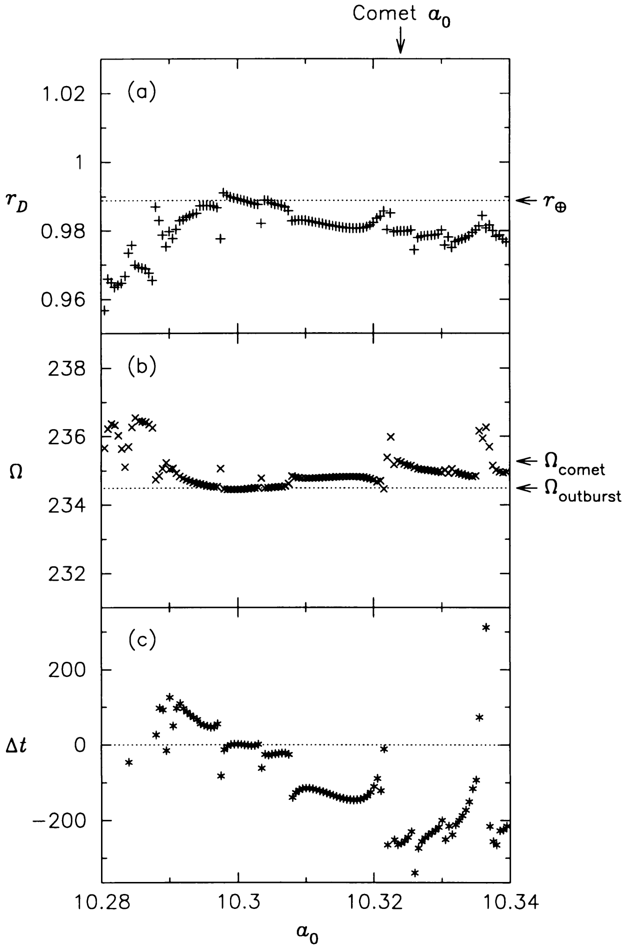

**Figure 3.** Orbital properties at 1998 November 17.1 of particles released at perihelion in 1333 September, versus initial semimajor axis $a_0$. The figure shows (a) the heliocentric distance of the descending node $r_{\mathrm{D}}$ (au) together with the heliocentric distance of the Earth $r_\oplus$ (dotted line); (b) the longitude of the ascending node $\Omega$, the dotted line corresponding to the solar longitude of the observed outburst (1998 November 17.1); and (c) the difference in time $\Delta t$ (days) of the nodal crossing of the particles from the time of the observed outburst. These results show that the conditions for meteors to be produced at the observed time are satisfied if $a_0 \simeq 10.30$ au.

Over most of the chosen ranges of $a_0$, no meteoroids could collide with the Earth in 1998 because conditions (i) and/or (iii) were not satisfied. Repeating the integrations with a finer grid of $a_0$-values, in steps of 0.0005 au, over all limited ranges of initial semimajor axis for which the preliminary integrations suggested that conditions (i) and (iii) might jointly apply, we found one particular set of particles, namely a subset of those released at the perihelion passage of 1333, which could collide with the Earth in 1998 (Fig. 3). This set of particles was unique in the range of $a_0$ over which both $r_{\mathrm{D}}$ and $\Delta t$ (Fig. 3) were close to the required values. For example, a subset of the particles released in 1433 (not shown in Fig. 3) apparently allowed Earth collisions in 1998, but only if $a_0$ was extremely finely tuned to take its appropriate value. This would mean that the resultant spatial density of particles in 1998 was substantially lower than for the 1333 particles.

Having identified, from conditions (i) and (iii) alone, 1333 as the perihelion passage with the dominant contribution to the 1998 fireball flux, we can check condition (ii) for those specific particles. The nearly regular nature of these resonant orbits means that $\Omega$ is now rather precisely specified, in contrast to the situation for chaotic orbits when after some time there is considerable dispersion in the ($r_{\mathrm{D}}$, $\Omega$) plane (Emel'yanenko & Bailey 1996). Based on our integrations, a fireball outburst owing to resonant particles would be predicted around $\lambda_{\odot} \simeq 234\overset{\circ}{.}5$ (Fig. 3), an outstanding match to the observed value and all the more impressive when noted as being of the order of a day earlier than passage through the orbital plane of the comet.

## 3 CONCLUSIONS

We have shown that the particles ejected from 55P/Tempel–Tuttle in 1333 with initial semimajor axes different from that of the comet by $\Delta a \simeq -0.024\,\mathrm{au}$ could intersect the Earth exactly at 1998 November 17.1 (Fig. 3). Such a change in semimajor axis corresponds to ejection of particles close to perihelion at a transverse velocity around $-2.4\,\mathrm{m\,s^{-1}}$, i.e. in the direction of motion opposite to the orbital motion of the comet. (Allowing for the small effects of radiation pressure on typical fireball-producing particles, this velocity increases to $\sim -4\,\mathrm{m\,s^{-1}}$.) Our results also show a probable additional contribution by large particles ejected in 1433, intersecting the Earth 2 h later, but involving significantly fewer particles than from the 1333 perihelion passage.

As to future events, the concentration of resonating particles, including the comet, has been carried along on its orbit and is now well past the Earth. The strong Leonid activity expected to occur in 1999 close to $\lambda_{\odot} \simeq 235\overset{\circ}{.}3$ (corresponding to 1999 November 18.1), and in 2000 close to $\lambda_{\odot} \simeq 236\overset{\circ}{.}3$ (2000 November 18.3), will be primarily due to meteoroids ejected from the comet in 1932, 1899 and 1866 (Brown & Jones 1996; Wu & Williams 1996; Yeomans et al., 1996; Kondrat'eva, Murav'eva & Reznikov 1997; Asher 1999). These particles are densely concentrated in space because they have had relatively little time since ejection to disperse. We predict that the population index of the 1999 Leonid shower should correspond to a normal population of fireballs. In contrast, the 1998 fireball outburst was due to meteoroids that were (i) generally larger, and so more likely to be injected into orbits nearer the comet (i.e. into resonant orbits), and (ii) concentrated in space many centuries after ejection owing to the dynamical properties of the resonance. The 1998 fireballs were thus an impressive observational demonstration of one of the most important dynamical features of meteoroid streams in Halley-type orbits.

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