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The dynamical structure of meteor streams and meteor shower predictions

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Abstract. Meteor streams that form as a result of cometary activity around perihelion consist of both structured and background components. The former are often referred to as trails. A trail is created at each perihelion passage as a result of the meteoroids' range of orbital periods. Trail locations can be precisely calculated by numerical integrations, allowing predictions of meteor outbursts and storms. The initial distribution of meteoroids, which relates to the meteor shower profile, depends on the meteoroid production rate and ejection velocity distribution as functions of heliocentric distance and on solar radiation pressure. The profile can gradually evolve owing to other radiative forces. This paper reviews such work on these aspects of shower predictions.

Keywords. Celestial mechanics, methods: numerical, meteors, meteoroids

1. Introduction

The science of meteor forecasting has more immediate practical applications than many topics in solar system dynamics, interested parties ranging from meteor observers to satellite operators. In common with other dynamical topics, stream modelling has benefitted from high speed computers, although distinctions can be drawn. Thus timescales for modelling relevant to meteor predictions are often short when compared against integration studies of various solar system populations, so that the required computation is less: apart from practical investigations of specific virtual impactors, asteroid and comet integrations using 'cloned' orbits usually cover quite long timescales. On the other hand, the practical need to map out extremely fine structure in streams can require more computation. Interest can nevertheless be focused on the fine structure in restricted regions of streams, such as those near the Earth or another planet, if computing power is limited.

Stages in stream evolution (from the early structured phases to dispersal within the same stream and thereafter beyond the original stream into the zodiacal background), and the dominant physical forces during different stages, are discussed by Williams (2002). Secular perturbation methods have been successful for constructing overall models of meteoroids gradually filling a stream (e.g., Babadzhanov & Obrubov 1987), especially when knowledge of the fine structure at precise locations is not needed.

As computing power has advanced, increasingly large scale integration studies have become possible (e.g., Brown & Jones 1998 modelled the Perseid stream, Vaubaillon 2003 the Leonids and π-Puppids). To obtain large statistical samples of particles, which greatly helps the examination of fine structure in a stream, there are also methods other than the direct integration of the equations of motion (e.g., see Ryabova 2001 on the Geminids).

Many of the most spectacular meteor storms have been found to be associated with meteoroids ejected at a single perihelion return of the parent comet. Many could be identified without building elaborate models of the meteor stream because, typically for some centuries after ejection, gravitational perturbations depend almost entirely on a single parameter (the orbital period immediately after ejection). The range of periods causes meteoroids to stretch into a long, narrow trail; a new trail is formed on each revolution of an active comet. Although recently most attention was given to the Leonids (e.g., Upton 1977, Kondrat'eva & Reznikov 1985, Kondrat'eva *et al.* 1997, Lyytinen 1999, McNaught & Asher 1999), a similar technique has been applied to many other streams (e.g., Davies & Turski 1962, Reznikov 1983, Reznikov 1993).

In what follows here, rather than the orbital period being referred to directly, the parameter a_0 is used. This is the semi-major axis when the meteoroid is released from the comet; Δa_0 is the difference from the cometary value. In cases where β (the ratio of solar radiation pressure to solar gravity) is non-zero, I define a_0 in terms of a particle with the same instantaneous position and velocity vectors moving purely gravitationally. Therefore in such cases the geometric semi-major axis (i.e., the semi-major axis of the ellipse corresponding to the path followed by the particle) differs from a_0.

To first order in computing dynamical evolution, the reason why any meteoroid has its given value of Δa_0 does not matter; while the physical cause of a_0 differing from the cometary value can be either velocities of ejection from the nucleus, or solar radiation pressure, the subsequent effect, through gravitational perturbations, is the same if Δa_0 is the same. Meteoroids with the same a_0, even if other elements are slightly different, co-move around their orbits, are therefore at a similar distance from each planet at every time, and so undergo identical perturbations. Planetary perturbations only differ significantly during close approaches to planets; it is then that substantial dispersion occurs (Asher 2002).

Usually the distance of a comet's node from the Earth's orbit is much greater than the width of a trail. Identifying parts of trails that come close to planets can be done by calculating the perturbations to the nodal position as a function of Δa_0. Without loss of generality, tangential ejection at perihelion can be assumed. The process of identifying the relevant parts of trails tends to be easy for young trails (a few revolutions), but gradually the various elements become less smooth functions of Δa_0 and detailed inspection of the values of orbital elements as functions of Δa_0 can become necessary.

2. Integrations

Modelling can be developed further by considering density distributions within trails, in particular cross sections at certain values of Δa_0. This is best illustrated using example integrations. Vaubaillon (2004, personal communication) found that meteoroids ejected from 55P/Tempel-Tuttle around its 1333 and 1733 returns would be perturbed so as to be moderately close to the Earth during the 2004 Leonid shower. I have therefore integrated particles based on those initial conditions (1333 and 1733) for illustration in this paper, although of course similar features are present in the Leonid and other streams whether or not the Earth is nearby. Integrations used the MERCURY package (Chambers 1999) implementation of the RADAU integrator (Everhart 1985) with 8 planets from Mercury to Neptune included (present day elements from JPL's DE403) and the cometary orbit from Nakano (1997). Plots shown below used isotropic ejection over the sunward hemisphere of 55P/Tempel-Tuttle but integrations with ejection over the whole surface of the nucleus gave very similar results. Meteoroid production was assumed to occur at $r < 3.4$ AU at a constant rate in true anomaly (i.e., faster near perihelion). The meteoroid ejection theory of Whipple (1951) developed by Jones (1995) predicts a dependence of ejection speed on heliocentric distance quite close to $v \propto 1/r$ and this is the relation used here. Generating sets of particles with different constants of proportionality demonstrates how cross sections relate to v (e.g., McNaught & Asher 2002). The extent of trail cross sections

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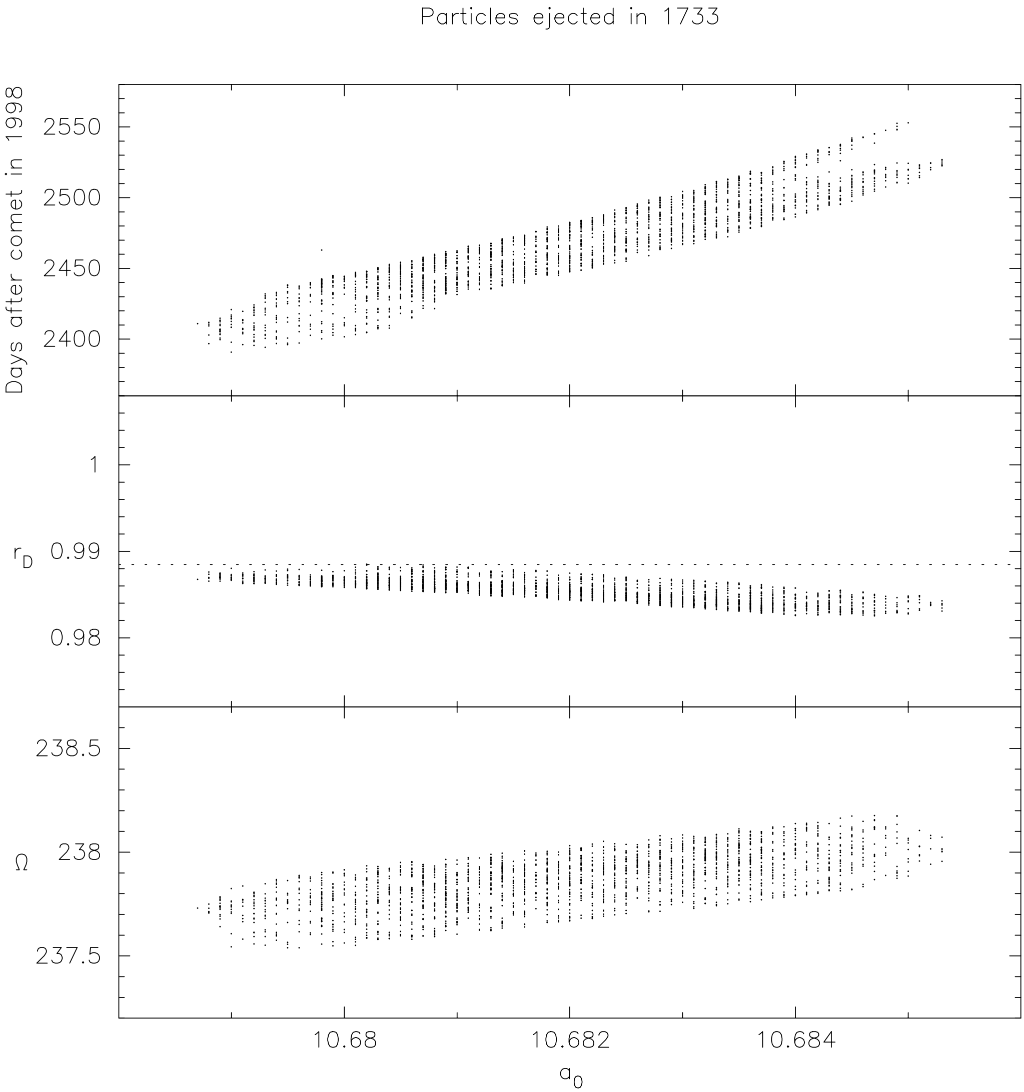

Figure 1. A short section of the 8-revolution Leonid trail in 2004. Particles that reach the ecliptic when the Earth is nearby are those whose nodal crossing is ~2450 days after that of the comet in 1998; this condition implies a narrow range of initial semi-major axis a_0, and other particles were not integrated. These particles had $\beta = 0$ (gravitational perturbations only) and $v = 50/r$ m/s. Elements in 2004 are fairly linear functions of a_0.

determines which trails are and which are not encountered by the Earth, and it is notable that observations and non-observations of meteor outbursts are in accord with Whipple theory.

Figure 1 shows particles ejected during a single perihelion return, with a single value of v_1 in the relation $v = v_1/r$ and a single value of β. The parameters r_D = heliocentric distance of the descending node (Earth's distance shown as horizontal dotted line), and Ω = longitude of ascending node, correspond to the two dimensions of the trail cross section in the ecliptic. Many other sets of particles, having different combinations of v_1

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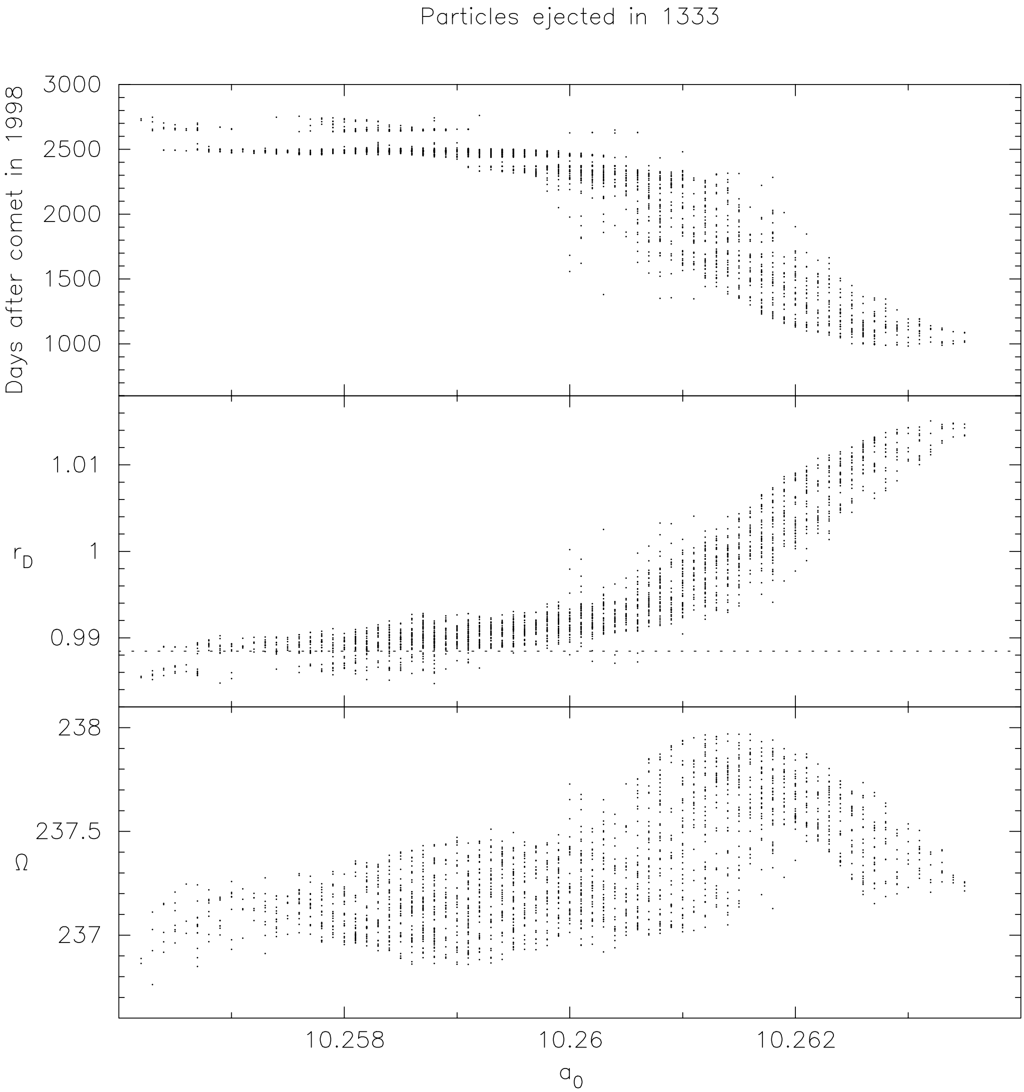

Figure 2. A short section of the 20-revolution Leonid trail in 2004. Ejection speed $v = 50/r$ m/s and radiation pressure parameter $\beta = 0.001$. The non-linearity here contrasts with a younger trail (figure 1).

and β, have been integrated, with the results similar except for the dispersion (i.e., the density distribution changes but the overall location in the ecliptic is very similar). The location of a given section of a given trail in space at a given time depends on the history of planetary perturbations starting at ejection time; that perturbation history is the same whatever the cross sectional density distribution, until that part of the trail is scattered. Figure 2 shows an older trail. The greater dispersion, and also the fact that even over a very small range the elements are not linear functions of Δa_0, can be seen. These features are present whether $\beta = 0$ or not.

Although the perturbation history determines trail nodal positions, in general planetary perturbations do not alter a trail's cross section for some time. Comparison of the

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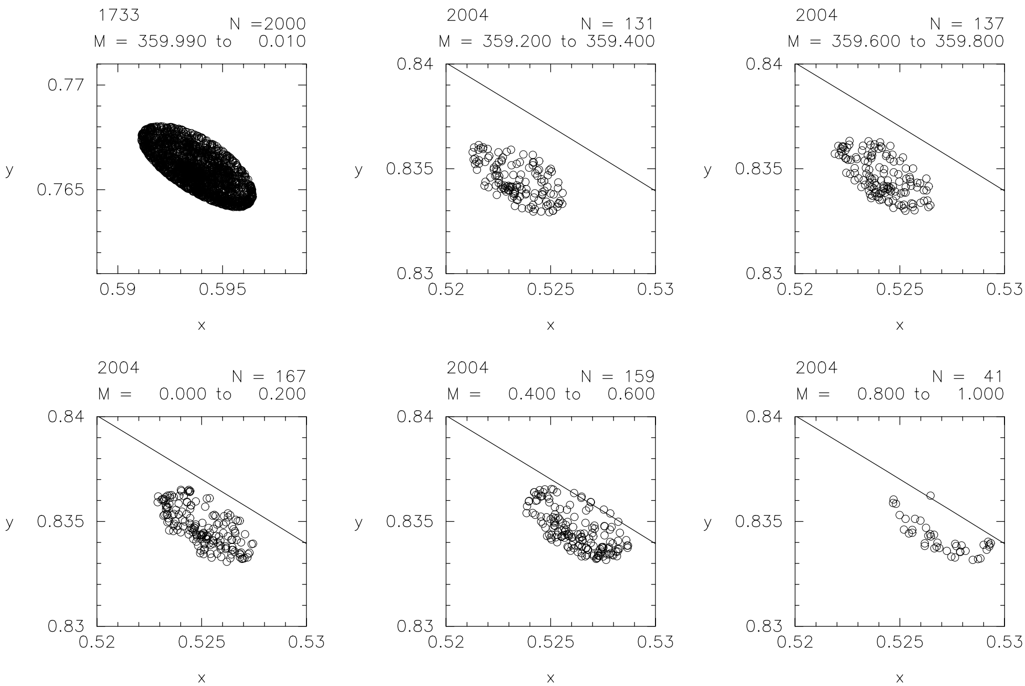

Figure 3. Cross sections in the ecliptic of the 8-revolution Leonid trail, near the part of the trail that the Earth approaches in 2004. Initial distribution in top left plot results from choice of $\beta = 0$ and $v = 50/r$. Remaining 5 plots are at roughly two week intervals in late 2004; the 3rd (i.e., left of bottom row) brackets the time when the Earth passes near. The line is the Earth's orbit.

top left panel of figure 3 with any of the remaining five panels shows that although the node has been shifted quite far (by $\sim$0.1 AU) during 8 revolutions, all particles at any single point along the trail are perturbed by almost exactly the same amount, so that the shape of the cross section is similar to the initial cross section. In a model involving gravitational perturbations and radiation pressure only, this is true for all v_1 and β. Additionally, comparison between any of those same five panels in figure 3 shows that the exact location in the ecliptic of a trail cross section is very sensitive to the position along the trail. Even a displacement a small way along a trail causes the perturbation history over several centuries to differ slightly. The lower total number of particles in the final plot of figure 3 is statistically significant: the trail has been more stretched along (but not across) the orbit at that point, diluting the number density.

Although, under gravitational perturbations alone, the dispersion eventually broadens after several centuries, cross sections within limited parts of trails can be maintained for some time. Thus in figure 4 the ecliptic crossing points of individual particles, at the same position along a trail, move relative to each other by small amounts over several centuries, up to about half the width of the cross section shown in that figure. These relative perturbations are a little more than for young trails, but insufficient to disperse that part of the trail into the Leonid background. Often resonances help to maintain compact structures in streams over substantial timescales (see Emel'yanenko 2001).

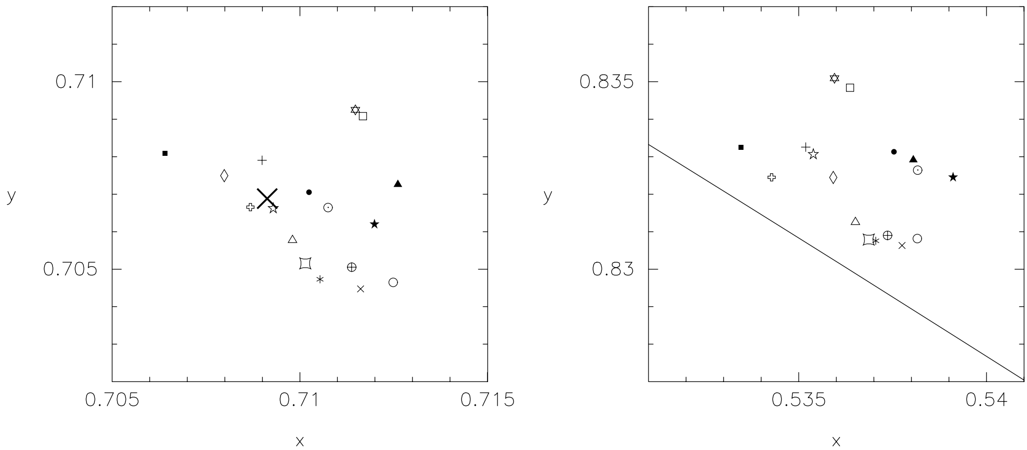

Figure 4. Example particles ($\beta = 0.001$, $v = 50/r$) in the 20-revolution Leonid trail, selected to be at a similar point along the trail, namely to cross the ecliptic within a few days of when the Earth (whose orbit is shown) is nearby in 2004. Each particle's nodal crossing point is shown with the same symbol in the left (ejection time) and right (20 revolutions later) plots. The large X in the left plot is the comet's node.

3. Discussion

Most of the sharpest meteor outbursts are due to meteoroidal material released just a few to several revolutions previously. Over these comparatively short timespans following ejection, orbital evolution under gravitational perturbations can be calculated precisely, as shown in § 2 and in references given above. Conditions for Earth impact at any given time can be constrained in terms of ejection with specific velocities and at specific true anomalies (e.g., Brown & Arlt 2000, Müller *et al.* 2001, Ryabova 2001, Asher & Emel'yanenko 2002).

However, a full description of a meteor activity profile requires knowledge of the initial conditions for the integrations (i.e., the distribution of particles ejected). The question also arises as to the effect of radiative forces (other than solar radiation pressure) on the orbital precession.

In principle, an activity profile can be constructed by the superposition of particles suitably distributed in v_1 and β (§ 2). Additionally the ejection model could be refined; for example, a distributed production model (Crifo 1995), in which fragments sublimate after being ejected from the cometary surface, may be more physically realistic. Ultimately, however, the question must be addressed of calibrating the model's prediction of activity profiles against observations. Difficulties can arise because of the effectively large number of parameters in the ejection model (even assuming any one comet shows the same activity pattern at each return); the distributions of particle sizes and ejection velocities can vary as functions of true anomaly.

Recently, the attempt by Vaubaillon (2002) to use observed meteor fluxes to calibrate predictions from dynamical simulations has met with significant success. This model uses ejection velocities given by Crifo & Rodionov (1997), and observations of the parent comet to constrain the dust production rate.

Modelling of other radiative forces has been done by Lyytinen & Van Flandern (2000) and Lyytinen *et al.* (2001), who have found good evidence that such effects have measurable observational consequences on the timing and strength of meteor outbursts. The

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most important force is a seasonal Yarkovsky effect but a neat feature of the model is that all the relevant forces can be incorporated into a single ‘A2’ parameter. Each individual particle’s orbit is systematically changed by radiative forces but different particles are affected to different extents (e.g., obviously not all particles have the same spin). The single parameter of the model is the width of the distribution of rates at which particles’ orbits are affected. The force, acting on all particles within trails, leads to a gradual spread in a trail cross section. Additionally, the component of the force that changes the orbital period has an indirect effect on the nodal position, through gravitational perturbations (the fact that the orbital change due to radiative forces is systematic meaning that the entire perturbation history of each individual particle is slightly changed). The name ‘A2’ for this effect is by analogy to the well known cometary A_2 acceleration (Marsden *et al.* 1973) in terms of the dynamical result, systematically changing the period (not, of course, in terms of the physical cause, which is different).

Recently most work involving the seasonal Yarkovsky effect has focused on bodies the size of asteroids or larger meteoroids (e.g., Vokrouhlický & Farinella 1999). Lyytinen & Van Flandern (2000) and Lyytinen *et al.* (2001) have considered the smaller grains that are relevant in the present paper: the sensitivity of trail perturbations over centuries to any small changes in the orbital period means that outburst timings can in some cases (especially for slightly older trails) be expected to shift by a few hours. The size of the A2 parameter can be calibrated by comparing model fits to observations. Just as ejection velocities determined indirectly from meteor observations are of comparable size to those predicted by Whipple theory (§ 2), good fits to observed meteor outbursts are found when the A2 parameter is of a size expected theoretically from consideration of seasonal Yarkovsky.

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