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Model predictions for the 2001 Leonids and implications for Earth-orbiting satellites

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ABSTRACT

A numerical model of the Leonid stream is developed, based on an earlier model which has been applied to the Perseid stream. The results for this model are applied to the 2001 Leonid return. By examining the full three-dimensional dispersion of individual 'streamlets' released from the Leonid parent comet, 55P/Tempel–Tuttle, we have derived an estimate for the temporal change in spatial density of each trail. Using this result along with an estimate for the location of the centres for individual streamlets and fits to previous Leonid storm profiles, we estimate that the activity from the shower will be broad and relatively strong (zenithal hourly rates perhaps in excess of 1000). In particular, streamlets from the 1766 and 1799 ejections contribute to activity peaking near 10 and 12 UT on 2001 November 18, respectively. Additional older material from 1633, 1666 and 1699, as well as more recent ejections from 1866 and 1833, contributes to a much broader secondary maximum near 17.5 UT on November 18. Comparison with other published models of predicted Leonid activity in 2001 shows general agreement in terms of timing, but the models differ significantly in terms of the relative magnitude of the activity (which other models suggest will be larger). Significant anisotropy in the impact hazard exists for satellites in the geostationary belt, with those over western longitudes most likely to be affected. Integrated fluences for the 2001 Leonid return suggest a hazard of order one magnitude greater than occurred for the 1999 Leonid storm.

Key words: comets: individual: 55P/Tempel–Tuttle – meteors, meteoroids.

1 INTRODUCTION

The Leonid shower has produced spectacular meteor storms for many centuries (cf. Brown 1999). Recently, the 1999 Leonid shower produced observed visual meteor rates in excess of 3000 per hour (Jenniskens et al. 2000) largely in accordance with predictions made just before the storm (Lyytinen 1999; McNaught & Asher 1999). This is the first time that a major Leonid storm has been accurately predicted.

The 1999 storm was caused primarily by particles ejected in 1899 (Kondrat'eva & Reznikov 1985; Brown & Jones 1996; Asher 1999), and this relatively young material is therefore less affected by accumulated planetary perturbations and other evolutionary processes. The very close passage of the Earth to such a young trail made it almost certain that a storm would occur.

In contrast, the Leonid activity in 2000 was the result of much older material ejected by the Leonid parent comet, 55P/Tempel–Tuttle, during its 1866 and 1733 passages, and therefore was both weaker and harder to predict. The modelled timings of the apparent peak activity by Asher & McNaught (2000), however, were very close to that observed (Arlt et al. 2000), although the magnitude of the peaks was more coarsely predicted.

In 2001, the Earth is expected to cross near the trails of several older Leonid ejections (cf. McNaught & Asher 1999). As a result, high activity has been generally predicted, although the precise magnitude and timing are dependent on determining the exact locations and extent of dust trails, which, again, are much older than was the case in 1999.

As a consequence we have attempted to model the Leonids using a variety of starting conditions, and follow the three-dimensional dispersion of the stream in an attempt to determine the relative decrease in spatial density for older streamlets. By applying this to our estimated miss distances for each trail, we hope to predict the approximate activity of the storm in 2001. We also briefly investigate implications of our model results and those of several other investigators for the satellite population orbiting Earth.

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2 APPLICATION OF A LEONID NUMERICAL MODEL

To simulate the formation of the Leonid stream, we adopt the same model of stream formation as used previously for the Perseids (Brown & Jones 1998). The basic procedure consists of generating a suite of test particles close to each perihelion passage of 55P/Tempel–Tuttle and following each of these through to the epoch of interest: in our case 2001 November. These ‘daughter’ Leonids are created through random ejection on the sunward hemisphere of 55P/Tempel–Tuttle and are distributed at random in true anomaly inside 4 au. The osculating elements for 55P/Tempel–Tuttle are taken from Yeomans, Yau & Weissman (1996). A total of 10 000 test meteoroids are ejected in each decadal mass interval from 10 to 10^{-5} g, for a total per perihelion passage of 70 000 test particles. This procedure is repeated for each of the last 15 perihelion passages of the comet so that each complete ‘run’ consists of just over 1 million test particles.

After the initial conditions are specified in this way, each test particle is numerically integrated forward from ejection to the epoch of interest and followed until it reaches its descending node (the only point along its orbit at which it might possibly be observable from the Earth) and its Keplerian elements at the time of nodal passage are stored. The integration includes the direct and indirect perturbations of all planets from Venus to Neptune, radiation pressure and the Poynting–Robertson effect. The integrator used is a fourth-order variable step-size Runge–Kutta (Jones 1985).

This basic procedure is repeated for four different physical models of ejection and three different values of meteoroid bulk density for a total of 12 different runs at each ejection. Our approach at this stage is to generate initial conditions that are ‘reasonable’ within the constraints of our imperfect understanding of the cometary coma dust environment, rather than to suggest any particular model as most appropriate. In particular, we recognize that there are large uncertainties in many of the physical quantities (i.e. density of meteoroids, relationship between meteoroid mass and luminosity, etc.) and choose instead to examine the effects of widely different (but still ‘reasonable’) ejection conditions (velocities, points of ejection and ejection directions) and meteoroid densities over a large range of masses in this Monte Carlo fashion. This approach has been used previously to study the formation and evolution of the Perseid stream (Brown & Jones 1998), and more extensive details and discussion can be found in that work.

To determine which test particles might be visible at the time of Earth’s crossing through the nodal region of the stream, we further limit our interest to only those Leonids that have nodal crossing times within 7 d of the Earth crossing the same solar longitude in 2001. The resulting distributions for each model and ejection epoch then constitute a ‘streamlet’ imprint of particles from a given ejection on the ecliptic plane having some spread in nodal radii from the Sun. The streamlet widths and positions relative to the Earth in 2001 are shown in Fig. 1 for ejections over the last 11 perihelion passages for all 12 models.

As can be seen in the figure, each streamlet has a differing nodal width depending on initial ejection conditions and the history of planetary perturbations experienced. To determine the probable peak flux and significance of each ejection, it is necessary to quantify the average decrease in flux at the node for the stream as a whole – that is, measure the dilution along the orbit (owing to spreading caused by differing periods), across it (owing to diffusion in the nodal longitude) and perpendicular to the stream orbit in a radial direction (owing to the spread in nodal distances).

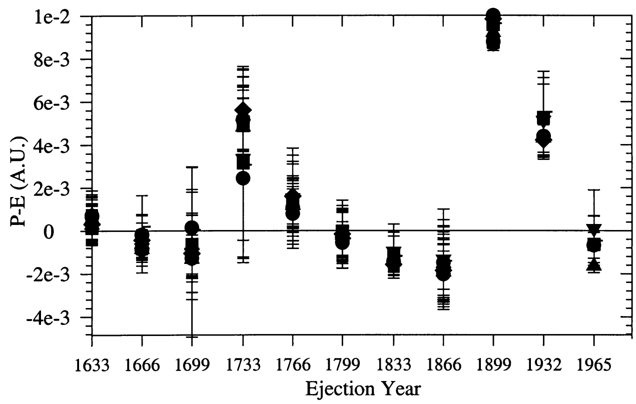

Figure 1. The distance from the Earth of various ‘streamlets’ ejected by 55P/Tempel–Tuttle in the years listed on the abscissa for test particles within 1 week of the time of the shower for 2001. Each symbol and vertical bar represent the mean and standard deviation of the particle population from 12 different models of initial conditions (see Brown & Jones 1998 for details).

To examine the question of diffusion in more detail, we have computed the average standard deviation of ascending node, nodal distance from the Sun and mean anomaly in the elements within the population of all visual-sized (mass $> 10^{-3}$ g) Leonid meteoroids in the streamlet (referenced to their nodal passages) for all initial ejection models in our simulation. Taking these three values and multiplying them together as a function of age gives a final relative change in the spatial density within the streamlet. The output for three typical models is shown in Fig. 2.

3 RESULTS FOR 2001

By taking the measured distance of the centre of each streamlet and using a polynomial fit to the density decrease as a function of age shown in Fig. 2, it is possible to estimate the time and relative magnitude of the peak flux in 2001 for each model based on fits to past Leonid storms. Note that we have assumed that the particles are distributed in a Gaussian manner in heliocentric nodal radius and nodal longitude about each average streamlet centre. We have used the most reliably determined past peak Leonid outbursts (those from 1966, 1999 and 2000) to determine the absolute level of the fits for each streamlet and each model, as our modelling provides only a relative measure of the density for each streamlet. We have performed fits of Leonid storms from 1966, 1999 and 2000 of the form $\mathrm{ZHR}_{\mathrm{obs}} = \mathrm{ZHR}_{\mathrm{max}} \exp\{-a[(r-b)/w]^2\}$, where $\mathrm{ZHR}_{\mathrm{max}}$ is based on the polynomial fit to the density decrease for each model, a is a free parameter, r is heliocentric distance, b allows for a systematic error in the radial geocentric distance of the streamlet nodal crossings, and w is a measure of the dispersion in the nodal radius. In this way we have found that the best fit to past observations is from model 12, namely one with distributed gas production in the cometary coma and a meteoroid density of $0.8\,\mathrm{g\,cm^{-3}}$ (cf. Brown & Jones 1998).

In particular, by matching the results from the 2000 Leonid return (cf. Arlt et al. 2000; Campbell et al. 2001) as shown in Fig. 3, we have been able to constrain the stream widths more precisely, and refine our estimate for the 2001 Leonid return.

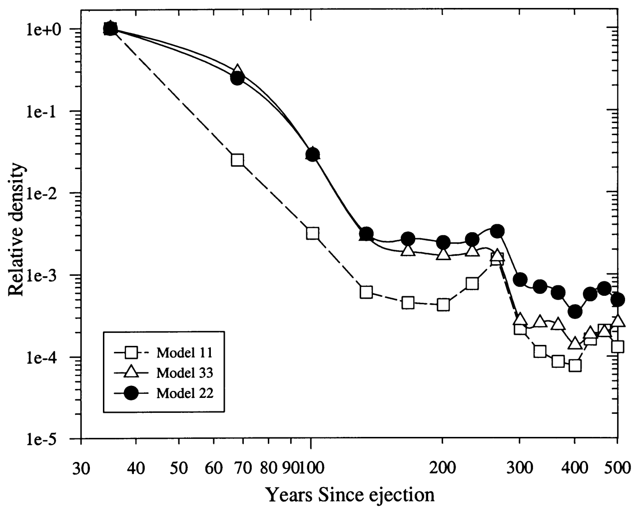

Figure 2. The evolution of the average relative particle density for meteoroids within the Leonid meteoroid stream, measured at the node, for models 11, 22 and 33 (see legend), illustrated by comparing streamlets of different ages. Model 11 is lower density particles ejected at very low velocities ($\approx 10\,\mathrm{m\,s^{-1}}$); models 22 and 33 are higher density particles ejected with a wider spread and larger values of velocity (10 to $100\,\mathrm{m\,s^{-1}}$). See Brown & Jones (1998) for more details.

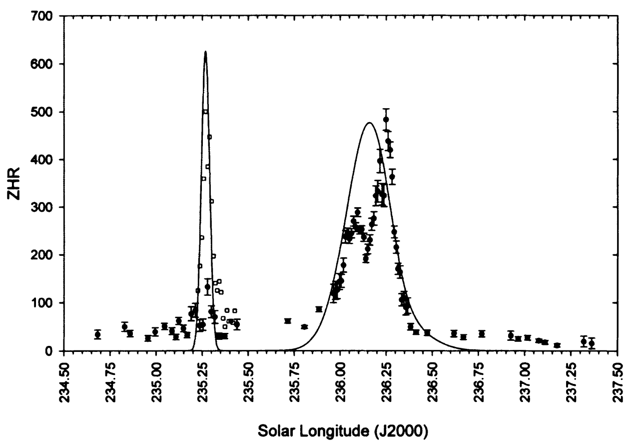

Figure 3. ZHR activity for the 2000 Leonids reported from visual observations by Arlt et al. (2000) (solid circles with error bars) and by Campbell et al. (2001) (open squares) from radar and electro-optical observations. Note the large difference in activity near solar longitude 235.25 indicating large numbers of smaller Leonids not detected by visual observers, associated with ejecta from 1932. The solid line is the model 12 fit to the observations from 2000.

4 COMPARISON WITH OTHER LEONID MODELS

Using the approach just described, the predicted activity profile from model 12 as a function of time near the 2001 Leonid peak is shown in Fig. 4. The modelled profile presented here is noticeably broader and weaker than that given by McNaught & Asher (1999) or that derived from the work of Lyytinen & Van Flandern (2000). This is due to the much broader streamlets associated with each

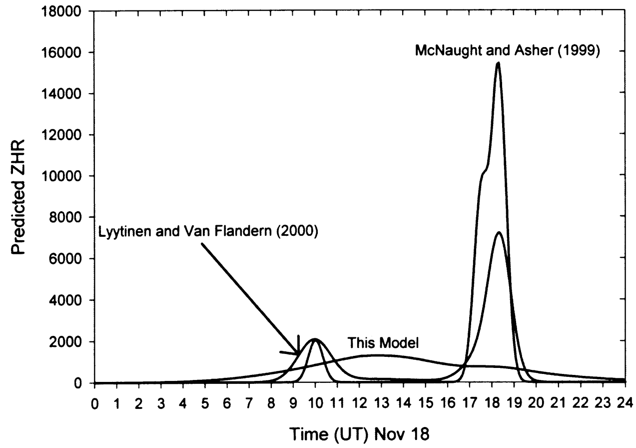

Figure 4. Predicted ZHRs for the 2001 Leonid shower. Shown are the predictions based on the model presented here, and those of Lyytinen & Van Flandern (2000) and McNaught & Asher (1999). For Lyytinen & Van Flandern (2000) and McNaught & Asher (1999) we have made use of their computations for trail centres and applied the ZHRs for historical Leonid returns given in Brown (1999) to compute the ZHR profile for 2001.

ejection epoch computed from our model, which takes into account the full dispersion in all three dimensions. In particular, the dispersion perpendicular to the orbital plane of the stream can be very large, an effect first noted by Kresak (1992). This is evident in the prolonged duration of the predicted activity in 2001 from streamlets that are relatively old.

It should be emphasized that while the timings for the peaks from specific streamlets are largely in agreement between the three models, the relative activities are not. This is in part a result of the fact that only one small segment of a given trail is sampled during any one Leonid return. A consequence of this sparse sampling is that the true peak densities are largely unknown and can only be approximately estimated by any of these models. Ultimately, the precise density is determined (in part) by the initial ejection conditions, which are not known.

Additionally, the varying approaches used for each model both for initial ejection conditions and to compute the stream centres (see Fig. 5) result in differing distances to each stream centre. In particular, the 1799 streamlet centre is much closer to the Earth as computed by our model, resulting in a relatively greater contribution of this streamlet near 12 UT on November 18 to our total activity than in either of the other two models. Based on these models, the times when enhanced activity might be expected (zenithal hourly rate, ZHR >500) range from 9 to 20 UT on November 18. The McNaught & Asher (1999) and Lyytinen & Van Flandern (2000) models predict strong localized activity near 10 UT on November 18, with ZHRs in the 1000–2000 range, and 17–18 UT on November 18, where these authors' predictions range from 7500 to 15 000. In contrast, our modelling suggests that the various older streamlets will blend together and produce longer duration and generally weaker activity with ZHRs no more than ~ 1500, peaking around 12–13 UT on November 18.

5 IMPLICATIONS FOR EARTH-ORBITING SATELLITES

To determine the impact risk to satellites, the ZHR profiles of Fig. 4 have been integrated and converted to fluences following the approach outlined by Cooke & Brown (1999); the results are given

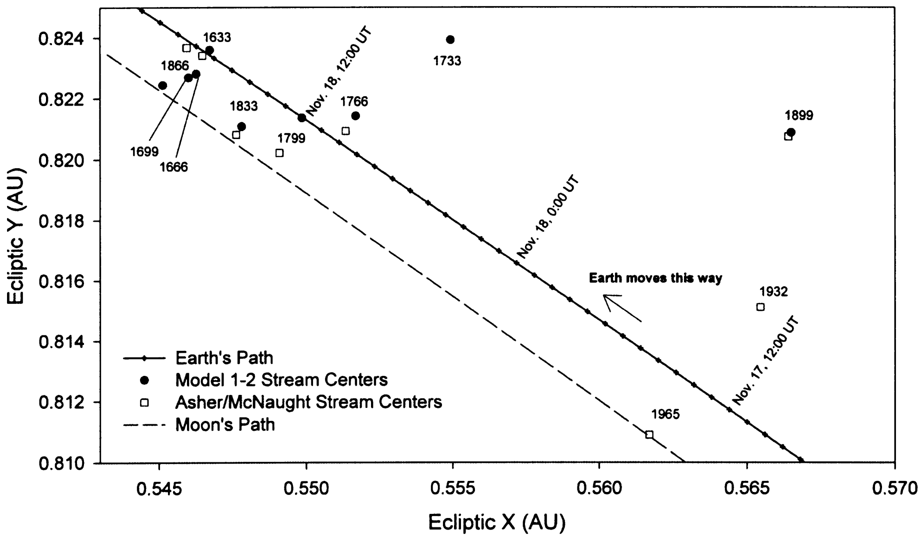

Figure 5. The relative stream centres predicted by our best-fitting model (12) and that of McNaught & Asher (1999) for 2001 November 18, projected on the ecliptic plane. The Earth's path is shown with ticks at 1-h intervals, while that of the Moon is given by the dashed line.

Table 1. A comparison of the predicted total fluences (to a limiting mass of 10 μg) for the 2001 Leonids, for three different dynamical models of the Leonids.

Model	Fluence (Leonids km^{-2})
This paper	6.6
McNaught & Asher (1999)	5.7
Lyytinen & Van Flandern (2000)	9.0

in Table 1. By way of comparison, the Leonid storm of 1999 had a fluence (over the whole duration of the shower) of just over one Leonid km^{-2}, and thus all models are predicting at least a factor of 5–9 higher fluence in 2001 relative to 1999. Put another way, the level of risk per satellite should increase by roughly an order of magnitude above that calculated for 1999.

As detailed stream locations and peak ZHRs are published for the McNaught & Asher (1999) model, they are used to compare with our calculations of Leonid fluences along the geostationary satellite band. Both models indicate significantly more activity for satellites located over the western hemisphere, with fluences (all fluences are referenced to a Leonid mass of 10 μg) as high as 8 Leonids km^{-2} and ZHRs approaching 20 000 Leonids per hour. Our model has the densest part of one stream, that generated by Comet 55P/Tempel–Tuttle in 1799, located right on top of geostationary orbit near 0°W (see Fig. 5), whereas the McNaught & Asher (1999) model indicates a more complex scenario, with three streams (produced in 1699, 1766 and 1866) interacting with satellites located over western longitudes.

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