ISSN 1016-3115

wgn

29-5
october 2001

bimonthly journal of the international meteor organization

The first *International Meteor Conference* of the new millennium took place in Cerkno, Slovenia, from September 20 to 23, 2001. The crowd was very international this year, with participants from four continents! The picture shows the participants in front of the hotel. More information *and* photographs from this conference can be found in this issue!

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v.u.: Marc Gyssens, Heerbaan 74, B-2530 Boechout, Belgium

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Useful Information

The December issue *(WGN 29:6)*

The *December issue* will be mailed around the end of December. Contributions should be sent as soon as possible to *Marc Gyssens.*

Subscriptions and ordering of publications

Volume 30 (2002) of *WGN* is expected to contain 240 pages and costs 20 EUR (subscribers paying before December 31, 2001, pay only 17.90 EUR or 35 DEM), including non-airmail delivery. Ordering other *IMO* publications is done in the same way as paying subscription/membership fees. Details can be found in this issue, on pp. 147–148.

Changes of address and complaints about not receiving *WGN* should be addressed to the Treasurer, Ina Rendtel.

All addresses can be found on the inside of the back cover.

From the Editor-in-Chief

Marc Gyssens

Since the last issue, the Perseids have passed. It seems that the "New Peak" has gone altogether now, although this conclusion is based on preliminary data only, and we should also keep in mind that the Perseids were badly affected by the Moon, this year. We anticipate to present a more comprehensive analysis in the near future.

Another important event was the annual International Meteor Conference, *this year in Cerkno, in the foothills of the Julian Alps, in Slovenia. As usual, it was a very invigorating experience to see each other again. A detailed report with some pictures can be found in this issue. New this year was that, for the first time, a larger group of meteor workers became aware of the necessity to involve more people in running the* IMO *for its longer-time survival. Time and again, I have stressed this point in my editorials, and I am of course pleased with this evolution. I can only hope that this people will now step forward and offer their help, either in the form of assistance in existing initiatives or in developing new initiatives.*

At least, it is encouraging that some new names figure in the list of candidates for the Council elections, for which members find a voting form in this issue.

Of course, the Leonids are the *event that preoccupies meteor workers the most these days, and this is, again of course, reflected in our journal. In the previous issue, Esko Lyytinen, Markku Nissinen, and Tom Van Flandern presented us their model, and in this issue, it is Peter Jenniskens's turn. In addition, Robert McNaught and David Asher are giving us—it is becoming a tradition—an update on their calculations, which started off the Leonid-mania in the first place!*

In all seriousness, now, whoever will turn out to have been the closest to the truth, the issue seems to be not whether there will be meteor storms, but rather how strong they will be. Several groups of observers have made plans to go to East Asia to find out, and, of course, the American peak also needs and will get the necessary attention. All this seems a bit discouraging for those observers who do not live on (one of the) right spot(s) or for whatever reason cannot afford to travel to one of these. They should not forget, however, that we also need data from the periods between peaks to get a representative profile of the entire *activity. The* International Leonid Watch *campaign, initiated within the* IMO *by Peter Brown, has resulted in a lot of data already and this collection needs further completion!*

Wherever you are, happy observing—as last year, we will try to keep you informed of the activity that materialized as fast as possible! Meanwhile, enjoy this issue!

Renew Your IMO Membership/WGN Subscription Now!

(With Answers to Some Frequently Asked Questions)

Ina Rendtel and Marc Gyssens

General information

After a long period of unchanged membership fees/subscription rates, we had to increase the price to 20 EUR/USD. Both printing and postage has become more expensive over the past few years, and we have no alternative but to reflect this in the dues.[1]

However, as an incentive to pay early, we offer you next year's subscription at the **old price**, that is provided you pay **before December 31, 2001**! You can even double your gain by paying for two years! Besides doing yourself a favor, you also help us by renewing early. In this way, we can keep our records straight, determine more accurately how many copies we need to print, and do not have to run on and off to the post office to mail back issues to late renewers!

In addition, you may also consider **ordering other IMO publications** (price list on outside back cover) to save on banking costs, because one payment is always cheaper than two! *New* IMO *publications* are Report 13 containing the 2000 visual observations, and the Proceedings of the 2000 and 2001 *IMC*s, the latter of which will appear in a few months, but can already be ordered now.

When you are interested in future Reports, we recommend you take a **combined subscription, which is cheaper than buying these Reports separately afterwards**!

[1] Due to the stability of the US Dollar over the last few years, we have *not* increased the USD rates; some rates may even have become cheaper! For simplicity, we have equated the EUR and USD rates.

We also increased the prices of some publications. When you order and pay **before December 31, 2001**, you may drop the pfennigs from the amount in German Marks, however!

Finally, you can **become a supporting member** by adding at least 10 EUR/USD per year to your membership (15 DEM or 7.67 EUR if you pay before December 31, 2001).

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For quite some time now, we have been offering the possibility to pay for two consecutive years, but people seem to forget whether or not they did so. **If the address label on the envelope mentions 2001, you should renew now!** People seeing a later year either have already renewed or paid for two years last year!

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Type of subscription	2002	2002 + 2003
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Also possible outside Europe:		
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Combined subscription with airmail delivery for *WGN* only	46.02 EUR (90 DEM) or 50 USD	92.03 EUR (180 DEM) or 100 USD

After December 31, 2001

Type of subscription	2002	2002 + 2003
Regular subscription (*WGN*)	20 EUR/USD	40 EUR/USD
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Regular subscription with airmail delivery	40 EUR/USD	80 EUR/USD
Combined subscription with airmail delivery for *WGN* only	50 EUR/USD	100 EUR/USD

Is there a difference between a membership and a subscription?

Yes, there is! **Both cost the same, but, to become a member, you need to fill out a membership application form.**

If you are not sure whether you are a member or a subscriber, look at the label on the envelope in which you receive *WGN*. If you are an IMO member, it says so on the label.

If you are not an *IMO* member and want to become one, you should fill out an application form. Notice that only physical persons can become *IMO* member. Because many people seem to be unaware of the difference between subscription and membership, we will print a membership application form in the February 2002 issue of *WGN*, which every subscriber who has paid his/her dues for 2002 will receive. **There is no reason to postpone renewal for subscribers who want to become member!**

The 2001 International Meteor Conference

Cerkno, Slovenia, September 20–23, 2001

Oliver Wusk

This year's *International Meteor Conference* (*IMC*) took place in the town of Cerkno in Slovenia and was the meeting place of international meteor observers from all over the world. The term "international" is well-chosen, because observers from many different nationalities attended the *IMC*. There were meteor workers from Argentina, Austria, Belgium, Bulgaria, Canada, Croatia, England, France, Germany, Italy, Japan, the Netherlands, Poland, Romania, Slovakia, the Ukraine, Yugoslavia, and, of course, Slovenia. In this respect, the *IMC* 2001 was a complete success.

The first evening was used for arrival and for check-in. The ensuing dinner was a welcome opportunity to talk to one another about various matters. During some time, about 25 participants were missing, because the shuttle bus to take them from the airport to the *IMC* did not show up. The mistake was corrected, luckily, and, later in the evening, they reached the meeting place.

On the next day, the *IMC* was officially opened by Mihaela Triglav, by Bojan Jenko and Domink S. Černjak from the Ministry of Education of Slovenia, and by *IMO* Council Member Marc Gyssens, who acted on behalf of *IMO* President Jürgen Rendtel who could not make it to the *IMC*. The program was filled to full capacity, and the coffee breaks and lunch were a period of welcome rest for the participants, as well as an opportunity to exchange ideas. A lecture well-worth to highlight was given by Jérémie Vaubaillon, who presented his first results of his program for "Leonid Observations and Dust Cloud Simulation." Furthermore, David Asher gave a short summary about this year's Leonids and what we can expect. He said, *You can sleep if you like, because you won't wake up with "Nothing will happen" because there will happen something* at the beginning of his lecture. The Polish observers presented their results of different September streams, including some which do not appear in the *IMO Working List*. First results were presented by Nikola Biliškov, who investigated the impact structure on Krk Island, Croatia. This investigation triggered off a discussion among our meteorite crater experts. One of the last lectures that day was given by Cathy Hall. She gave a slide presentation of the meteor roots of Canadian observers, and showed in particular how she got into meteors. Dinner was again used for discussion.

During dinner, two people were missed that were supposed to come—Daniel Fischer and *IMO* Council Member and Video Commission Director Sirko Molau. Sirko had a good reason for not being there: he was simply not allowed into the country by the Slovenian authorities. Why? Because both his identity card and his passport had expired! Surely, Sirko will double-check his documents the next time he travels! After dinner, Rainer Arlt's workshop "*VMDB* and analysis" took place. The main topic was that the *VMDB* desperately needs more hands to deal with the large amount of data. Rainer is searching for help to feed the computer with the data and to develop a new form for the *VMDB*. After 12 hours of lectures, all participants relaxed with beer or wine, although some of them preferred their bed.

Figure 1 – The lecture room during the official opening. In the middle of the picture, the representatives of the Slovenian authorities can be seen.

Figure 2 – The Triglav sisters: Gabrijela to the left; Mihaela to the right.

The next day started with breakfast at 8 a.m. After that, there were again a lot of lectures. Juan Martín Semegone from Argentina held an interesting lecture on his group's devoted radio set-up. Having already built a receiver specifically optimized for radio meteor observations, they are now in the process of building an equally devoted receiver to perform high quality radio observations. Peter Zimnikoval from Slovakia presented a "TV spectrum of a meteor" and Felix Bettonvil from the Netherlands thought about some possibilities a meteor observer can consider when he or she is tormented by city lights. These possibilities included going into local politics, giving up your hobby altogether, or becoming a video meteor observer. Felix decided to become a video meteor observer, and showed his first results.

Next point on the program was the *IMO* General Assembly. During this meeting, acting President Marc Gyssens emphasized again the need for more people to take part in *WGN* by writing articles or participating in the editing process, and also for more people to help with the *VMDB*. Furthermore, Marc recalled last year's efforts with regard to the Leonids.

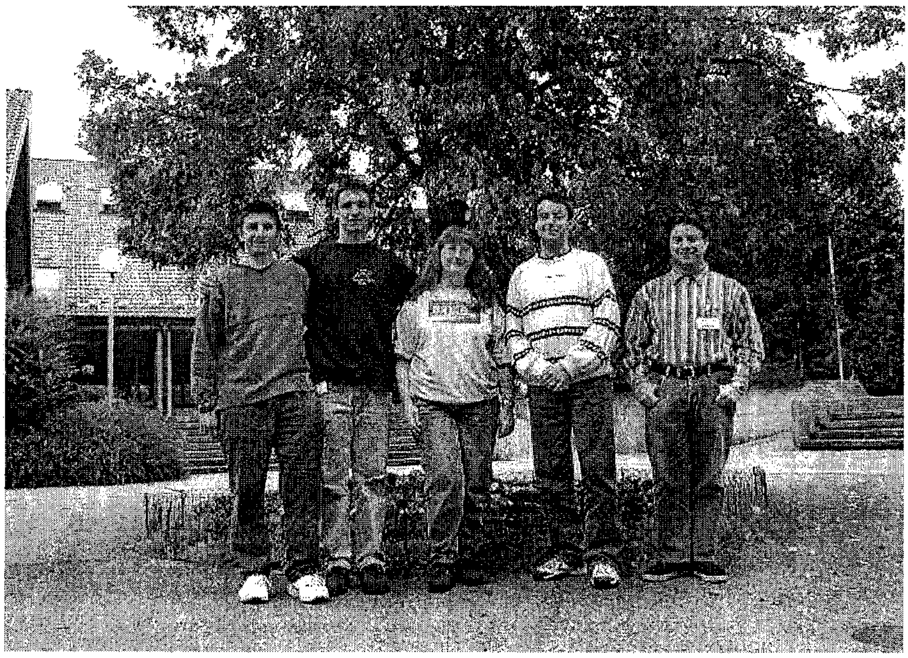

Figure 3 – Jure Zakrajšek, Jure Atanačkov, Javor Kac, and Mirko Kokole, all from Slovenia, surrounding Cathy Hall, from Canada.

The *Fireball Data Center* (*FIDAC*) needs help as well, because there is a lot of data, and it is just too much for one person to deal with. André Knöfel considers lowering the cut-off magnitude for a fireball from −3 to, e.g., −5. This is definitely worth considering.

The next topic at the General Assembly were the finances, which are healthy. The membership fee for 2002 will be 20 EUR, but people paying before January 1, 2002, can still take advantage of the old rates!

This issue of *WGN* will contain a ballot form for the next *IMO* Council elections. Except for André Knöfel, all present Council members are re-eligible. Particularly well-received were the first-term candidacies of Mihaela Triglav and David Asher.

At the end of the meeting, the location of the 2002 *IMC* was discussed. There is a choice between Poland and Jordan. More details of the proposals are awaited by the end of October, after which the Council will make a decision.

After lunch, the traditional excursion led all participants to the famous Postojna Caves, which are not that far from Cerkno. This cave system consists of 7 caves and is 21 kilometers long. We visited the Postojna Caves and went 4 kilometers into them, the first 2 kilometers with a special train and the rest on foot. All participants were impressed by such beauty. It was one of the best excursions since years. After one and a half hour in the caves with faint light and 10° C, we drove back to Cerkno.

The breathtaking excursion was followed by a breathtaking dinner. Then the Romanian observers gave their traditional astropoetry performance, directed by Andrei Dorian Gheorghe. As always, the show was well-liked among the participants. Afterwards, Mihaela treated us to wine, and, realizing that this was our last evening together, there were a lot of discussions and laughter and picture-taking.

In the morning of the following day, the Romanian observers presented their "Meteor Art at *IMC*'s before the third Millennium." After some microphone breakdowns, the *IMC* was successfully closed by Marc Gyssens with the words *see you next year*.

Altogether, the *IMC* was a great success this year with around 70 participants from all over the world. I want to emphasize that the organizing committee consisting of Mihaela and Gabrijela Triglav, Jure Zakrajšek, Jure Atanačkov, Javor Kac, Nico Štritof, Urška Pajer, and Stane Slavec did a great job, and they tried to make everything as comfortable as possible for the participants. Thank you very much. See you next year at the IMC 2002.

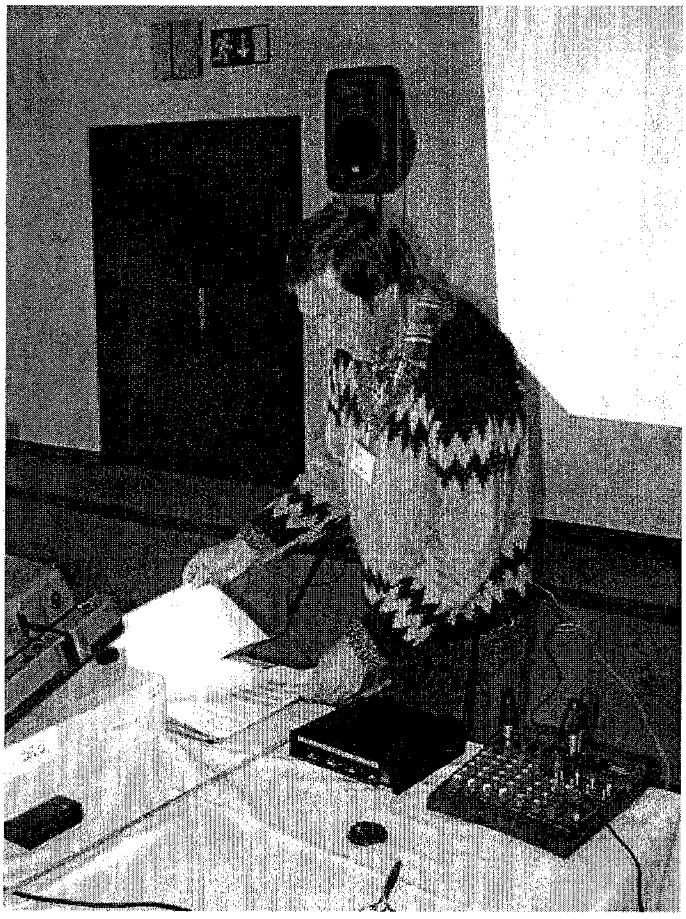

Figure 4 – Peter Zimnikoval (Slovakia) during a lecture.

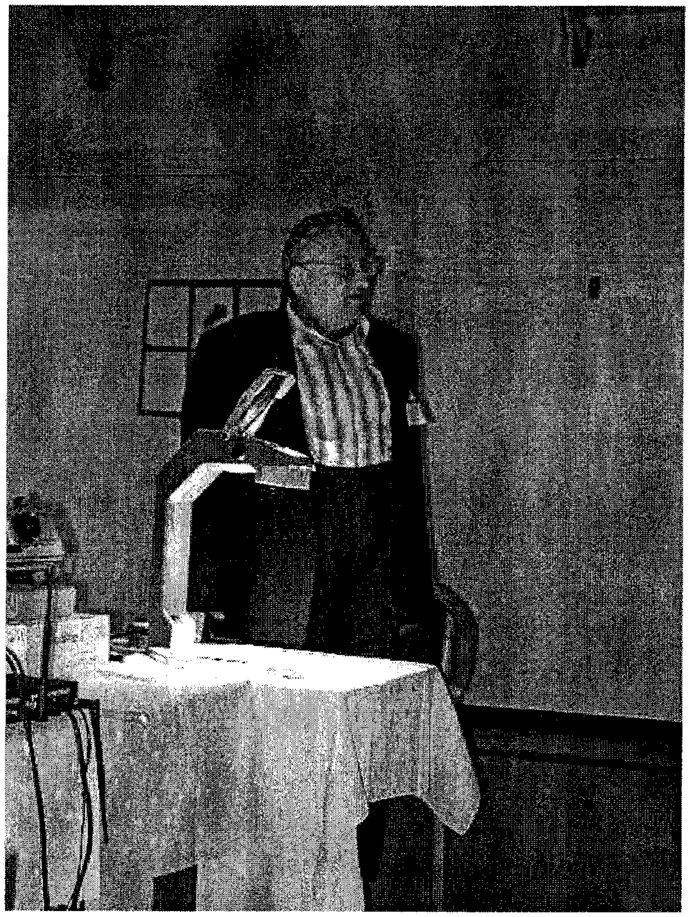

Figure 5 – Vladimir Smirnov (the Ukraine) during his talk.

Figure 6 – Close-up of Juan Martín Semegone (Argentina) during a coffee break.

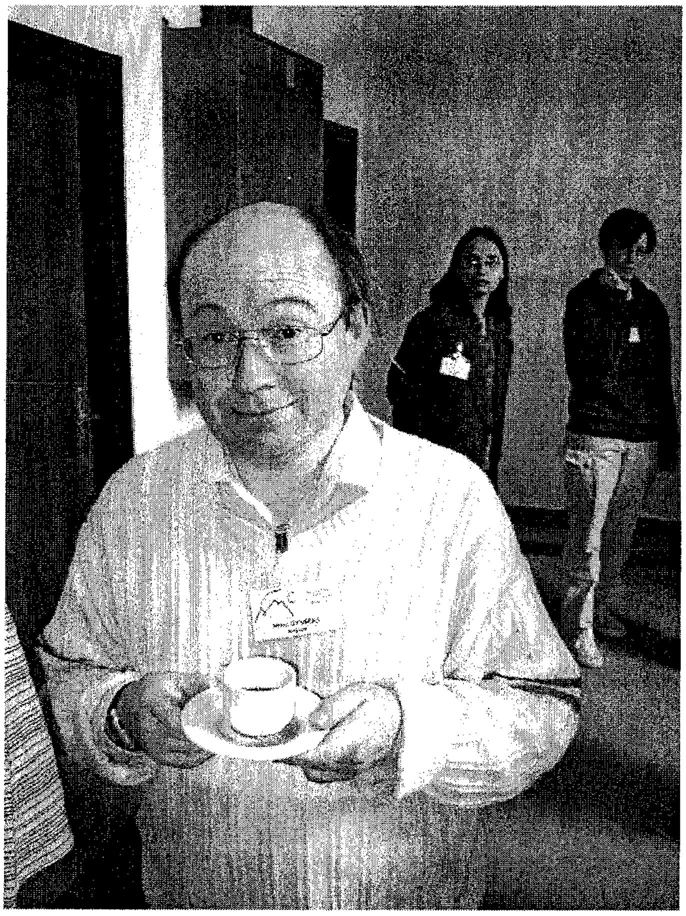

Figure 7 – *WGN* Editor-in-Chief Marc Gyssens (Belgium) desperately tries to keep the coffee in his cup!

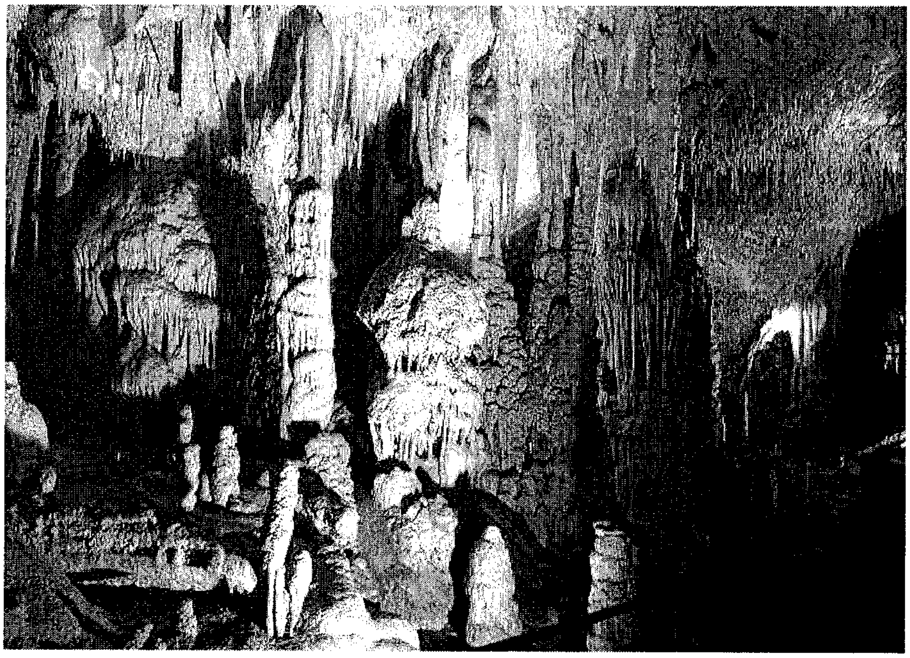

Figure 8 – The amazing Postojna Caves.

Figure 9 – David Asher (Armagh Observatory, Northern Ireland), Dragana Okolić (Yugoslavia), Felix Bettonvil (the Netherlands), and Irena Živković (Yugoslavia), at the entrance of the Postojna Caves.

Figure 10 –The blissful smile of Cis Verbeeck (Belgium) at the get-together in the bar during the last evening says it all!

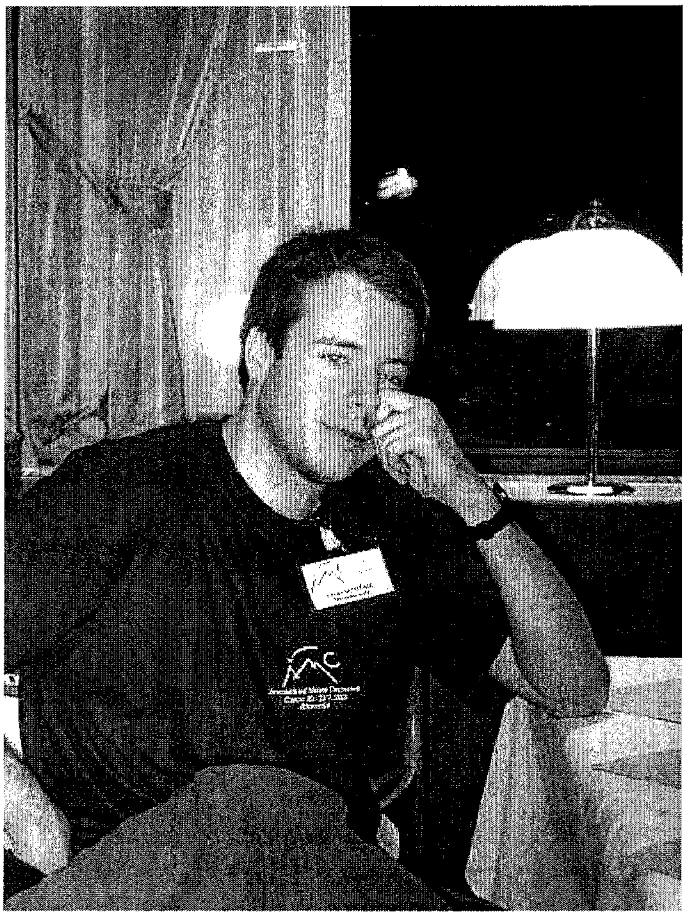

Figure 11 –Tired, but satisfied: Javor Kac (Slovenia).

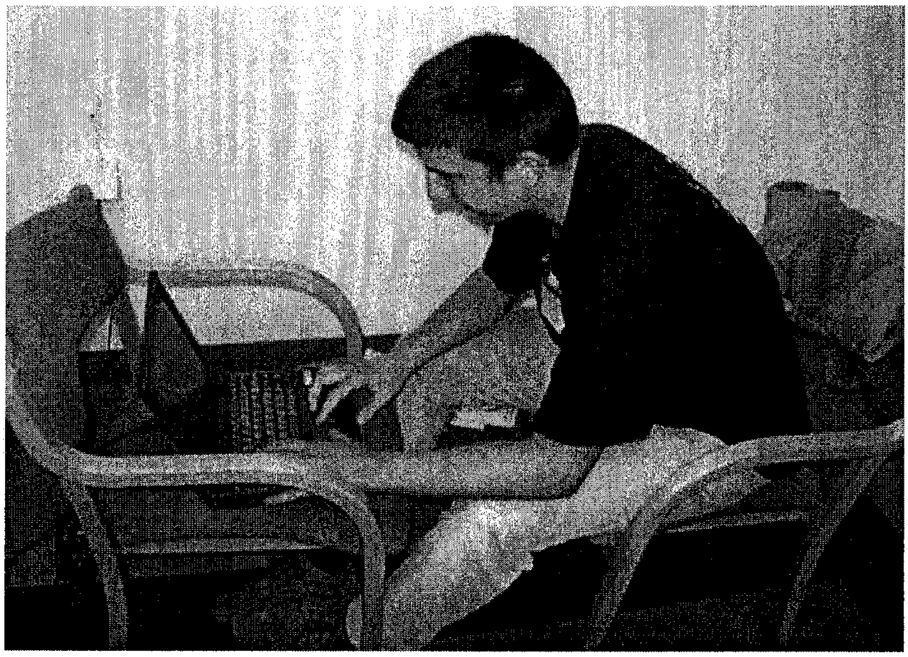

Figure 12 –No rest for the wicked: Jure Zakrajšek is working around the clock on his laptop to get the pictures processed and the web page updated!

Leonids

The 2001 Leonids and Dust Trail Radiants

Robert H. McNaught and David J. Asher

On 2001 November 18th UT, the Earth will have close encounters with trails of meteoroids and dust generated over the past few centuries by Comet 55P/Tempel-Tuttle. It has previously been shown that these trail encounters will produce spectacular meteor displays, observers at east Asian longitudes and in North America having the chance to see this year's Leonid activity peaks in a moonless sky. Work by Lyytinen et al. has discussed the relevance of dispersive radiative effects in trail aging. In this article, we find that combining our existing ZHR model with an empirical aging parameter still leads to expected rates of several thousand from the east Asian trail encounters. We also consider what may be learned from high-resolution observations of radiants during such outbursts, of particular interest in 2001 because of meteor activity expected simultaneously from more than one trail. The Leonid radiant structure is shown to contain radiants from each dust trail separated by several arc minutes, and moreover each dust trail radiant contains its own internal structure which relates to the Comet's activity during the perihelion passage when the trail was generated.

1. Dust trail theories

Leonid meteor storms in November 2001 are now widely expected. These will occur when the Earth passes through dense, narrow trails of meteoroids and dust embedded in the Leonid stream. Several such trails exist, one being generated each time Comet 55P/Tempel-Tuttle returns to perihelion every 33 years or so, and typical lifetimes for trails' survival as narrow, coherent structures being of the order of a few centuries. The trails form and gradually lengthen because they consist of meteoroids having a range of orbital periods, particles of shorter and longer period progressively getting further ahead and behind, respectively.

As any one trail is much narrower than the whole Leonid stream, the Earth will usually miss most of the trails by a significant distance when it passes through the stream each November. However, trail positions are continuously shifted by gravitational perturbations and so it is necessary to evaluate these perturbations in order to see whether any trails are, in November of a given year, shifted to lie very close to the Earth's orbit. This would allow them to be encountered by the Earth, i.e., a high density of particles to impact the Earth's atmosphere and a meteor storm to be produced.

To determine trail positions with sufficient accuracy that all occurrences and non-occurrences of Leonid storms over the past two hundred years are correctly explained, it turns out to be sufficient to vary only one parameter. That is, ejection at perihelion is assumed and only the orbital period (at the time of ejection) is varied. For example, to determine whether meteoroids released from the Comet around its 1866 return (4 revolutions ago) come near the Earth in November 2001, particles ejected exactly at the instant of the 1866 perihelion passage are considered over a range of orbital periods and their evolution under gravitational perturbations (and, optionally, solar radiation pressure) through to November 2001 is calculated. An orbital period at the 1866 perihelion is determined that causes particles to reach their descending node in November 2001. If such particles cross the ecliptic at a heliocentric distance that is close to the Earth's orbit, then meteors will be produced. Moreover, the longitude at which they cross the ecliptic will correlate with the time at which the meteor outburst occurs. Calculations using essentially this technique have been performed by various groups and similar results have been derived (e.g., see [1–3]; the reader is also directed to these papers for references to earlier work).

Such calculations showed, for example, that the Earth encountered the 1733 (8 revolutions old) and 1866 (4-rev) trails in November 2000, but that the Earth missed the nominal centers of the trails by some distance. The peak ZHRs were therefore in the hundreds [4] rather than matching the levels reached in genuine meteor storms.

2. Leonids 2001 and ZHR fit including aging parameter

The dust trail technique predicts closer encounters of the Earth with Leonid dust trails in November 2001 than last year, leading to enhanced Leonid activity observable from North America and later from East-Asian longitudes on November 18 UT, 2001. The reliability of such predictions, firstly as regards the timings of peak activity, and secondly as regards the activity levels, is evidenced by the successful application of so-called dust trail models to all sharp Leonid outbursts in the past for which accurate observational data exist. We have previously mentioned that the idealized model (ejection from the Comet at perihelion in a fixed direction) might be imperfect for the encounter with the 7-rev trail (North America), because nearby points along that trail have been gravitationally disrupted during the intervening two centuries. Nevertheless, the chances are that the relevant part of the trail has survived as a dense, compact structure, so that the North-American outburst should occur.

The question of whether a higher ZHR will be observed during the earlier (North America) or later (East Asia) storm has received much attention. Results derived using a fuller model of ejection from the cometary nucleus [5] show enhanced meteor activity due to the same trail encounters found by the simpler idealized model. Reference [5] suggests the 6-rev and 5-rev encounters at intermediate times are also significant, leading to the activity profile being filled in over the intervening hours (between North America and East Asia). However, although some interaction with high velocity ejecta from 55P/Tempel-Tuttle 6 and 5 revolutions ago is likely, the moderately large miss distances calculated using the dust trail technique suggest no storm level activity from those encounters.

Table 1 – Parameters of Leonid trail encounters in November 2001 and 2002. Δa_0 specifies the point along the trail, given in terms of the semi-major axis difference from the Comet at the ejection epoch; the mean anomaly factor f_M is the inverse extent to which originally nearby particles have separated in the along trail dimension, at that point (negative f_M means mean anomaly is an increasing function of Δa_0); and $r_E - r_D$ is the distance in AU by which the Earth misses the nominal trail center (descending node of trail particles). This year, the Earth appears to encounter nearby but distinct points along the 7-rev trail. The ZHR fit is based on trail age, Δa_0, f_M and $r_E - r_D$, using data from 1866, 1867, 1869, 1966, 1999, 2000/4-rev, and two 2000/8-rev trail encounters close in time with assumed maximum ZHR of each equal to 135. A background ZHR of 30 is removed from all the 2000 dust trail ZHRs, the background becoming a significant contaminant of the dust trails with low ZHRs. The final decimal in these numbers is highly sensitive to the orbit adopted for the Comet.

Time (UT)	Trail age	Δa_0	f_M	$r_E - r_D$	Fitted ZHR
2001 Nov 18.382 (09^h10^m)	7-rev (a)	+0.096	−0.003	−0.00086	2
2001 Nov 18.413 (09^h55^m)	7-rev (b)	+0.085	0.156	−0.00048	800
2001 Nov 18.458 (11^h00^m)	7-rev (c)	+0.072	−0.005	−0.00010	70
2001 Nov 18.725 (17^h24^m)	9-rev	+0.046	0.401	+0.00010	2000
2001 Nov 18.733 (17^h36^m)	11-rev	+0.029	−0.022	+0.00020	40
2001 Nov 18.759 (18^h13^m)	4-rev	+0.146	0.139	+0.00018	8000
2001 Nov 18.780 (18^h43^m)	10-rev	+0.035	−0.011	+0.00004	40
2002 Nov 19.162 (03^h53^m)	7-rev	+0.117	0.132	−0.00013	3000
2002 Nov 19.437 (10^h29^m)	4-rev	+0.177	0.152	−0.00004	10000

For forthcoming encounters, we have derived a new fit of the peak ZHR to the miss distance $r_E - r_D$ and other parameters (Table 1). While the spatial density of particles varies in the across trail dimension, as parameterized by $r_E - r_D$, there is also a density variation in the along-trail dimension. We have previously used Δa_0 (Table 1) as the parameter for the latter, particles on smaller orbits having shorter periods and, therefore, moving towards the front of the trail (and vice versa). The along-trail density is expected to rise to a maximum, basically because the orbits of meteoroids will concentrate towards the orbit of the Comet, but the maximum in reality tends to shift behind the Comet, owing to solar radiation pressure. That shift is expected to be by an amount equivalent to Δa_0 of the order of +0.2 AU or so, for millimeter-sized particles (visual Leonids).

Thus, the particle density essentially depends on two spatial (along and across the trail) parameters Δa_0 and $r_E - r_D$. It also has a time (evolutionary) dependence. In our previous work, we only considered stretching of the dust trail as the aging effect. This was the f_M factor (Table 1) which is derived directly from calculation rather than having a density dependence fitted empirically. The cross-sectional profile of the trail is largely invariant under gravitational perturbations, and so this stretching is along the trail (to a simple approximation linear with age, but evaluation of gravitational perturbations allows an exact value to be found at a given point along a given trail). However, it is expected that additional non-gravitational factors will act to diffuse the dust trail cross-section [3]. An additional aging factor for the dispersion within the trail cross-section would have the density of an n-rev trail decreased by a factor y^{n-1} compared to a 1-rev trail, where y would be 1.0 if the cross-section were unchanging. Adding this parameter and including the *IMO* ZHR data for the 2000 4-rev and 8-rev trails gives $y = 1.38$. In fact, similar results are obtained excluding the 2000 4-rev and 8-rev encounters.

Attempting to include the 2-rev encounter from 2000 which occurred at the rather large distance $\Delta r = -0.0012$ reduces predicted ZHRs by a factor of about 3, but also spoils the fit to past data, particularly for 1966. Our model does not appear to extend to such values of $r_E - r_D$, and, especially for the close encounters of 2001 and 2002, it is more important to fit the storm region than the periphery. According to this fit, then, 38% of the ZHR is lost from revolution to revolution owing to diffusion in the cross-section. The ZHRs resulting from the fit done in this way, a topocentric correction having been applied to the past encounters, are listed in Table 1.

While working on this updated ZHR fit, we came across a few other points worth mentioning, from the calculations that determine trail encounter parameters ($r_E - r_D$, etc.). Multiple encounters, overlapping in time, with nearby but distinct points on the 8-rev trail occurred in 2000 (see also [3]); cf. 7-rev in 2001 in Table 1. Calculated times, not in Table 1 which only gives future encounters, are November 18, 2000, 3^h23^m and 3^h33^m UT, with a third encounter giving significantly lower rates about 20 minutes later. It is emphasized that these timings are dependent on the orbital solution for 55P/Tempel-Tuttle, which is the essential input to the calculations. In this paper, we use the orbit computed by Nakano in *Minor Planet Circular* 29285 from observations covering 1366–1997. The Comet's orbit over many centuries is known very accurately, but variations in cometary non-gravitational forces over this time scale allied with tiny astrometric uncertainties mean that the orbit can never be known to infinite precision. Therefore, while outburst timings can be predicted to an accuracy of several minutes, the times in Table 1 may differ from values we and others have published elsewhere.

For example, a different input orbit yields times 9–10 minutes later than the above for the 8-rev trail in 2000. A maximum recorded by video from an aircraft [6] with a peak at November 17, 2000, $7^h48^m \pm 4^m$ UT is close to times we find for the somewhat distant 2-rev encounter, 7^h45^m and 7^h51^m UT for two Comet orbital solutions. The 4-rev trail was less well defined in the visual data from November 18, 2000, but appeared to arrive some tens of minutes earlier than the 7^h41^m or 7^h51^m UT that we now calculate. This may be due to systematic radiative effects [3], and also peaks may be less sharply defined when the Earth's passage through trails is away from their compact cores. The fit to the two stronger 8-rev encounters in 2000 indicates these had the same strength. The mid-time of these theoretical peaks is 3^h28^m UT, very close to the observer peak time of 3^h24^m UT [4]. This passage too was away from the core of the trail, but a tentative interpretation might be that the orbit utilizing the 1366 observations better represents the Comet's orbit for calculations involving old dust trails. The timing of young dust trail encounters is likely to be better than older ones for three reasons.

As noted below, dispersive effects may shift the peak time for older trails, and, with such broader activity, the peak also becomes more difficult to define from observation. Additionally, the younger dust trails involve ejection during the period for which the Comet's orbit is best defined, so that errors in the starting orbits of the ejected dust are smaller.

An additional factor affecting the ZHR fit is the position of the peak density in heliocentric radial distance, i.e., whether the maximum is displaced from the value of r_D calculated in the idealized model. We discussed that in our original paper, suspecting that the trail center might be displaced further from the Sun. Jenniskens [7] has argued that the trail center might be displaced closer to the Sun giving a peak at $\Delta r < 0$. However, this may be dependent on the assumption made by various authors (see below) that the profiles in the $r_E - r_D$ and ZHR dimensions are of the same form. Adjusting the value of r_0 (the dust trail center in heliocentric radial distance), in the fit that included the aging parameter, shows a pronounced minimum in the residuals around $r_0 = 0.0000$. Thus we find no evidence of any significant shift of the dust trail center. It should be noted that the relative strength of the 4-, 7- and 9-rev dust trails in 2001 is very sensitive to r_0, although even with r_0 shifted by -0.0004 AU, the North-American encounter never goes above a ZHR of 1000 in this model nor does it reach the highest East-Asian peak.

In all, various ZHR estimates for the peak activity due to the main trail encounters in 2001 have been published, e.g., [2,3,5,7] and Table 1 of this paper. These are calibrated using past Leonid data, and are referenced to dynamically realistic models (even if, e.g., the ZHR estimate does not come *directly* from a dynamical calculation of a dust trail position). There is, therefore, reason to regard them as reliable, although differences among the various estimates demonstrate the model dependence of the predictions. This model dependence can be contrasted with calculations of gravitational perturbations, the great success of Newtonian gravitational theory having been demonstrated for three hundred years. Leonid storm predictions neglecting planetary perturbations have about as much predictive power as astrology.

The results in Table 1 were calculated using gravitational perturbations *only*. Such results have been shown to apply to a high degree of accuracy for the sharpest Leonid outbursts of the past two hundred years. However, certain radiative forces might act systematically over a few centuries [3], causing a displacement in the time of peak meteor activity. This may be of the order of 20–30 minutes for the 7-rev and 9-rev encounters. These times are expected to be measurable observationally and should be among the many interesting results this November. Such differences in the modeling have little effect on what part of the world one decides to observe from, however. Similarly, while a moderate number of meteors from the 10-rev and 11-rev trails should be detected, anyone observing 9-rev and 4-rev meteors from East-Asian longitudes should experience the 10-rev and 11-rev encounters automatically.

We have considered a more general approach that would allow a fit of various ejection models to the observed peak ZHRs, outburst widths and mass distributions, but it was too involved to complete for the 2001 Leonids. Nevertheless, we note that in [3,5,7] it is assumed that the profile of a dust trail in heliocentric nodal distance ($r_E - r_D$) is of the same form as the ZHR profile, with different authors favoring a Lorentzian or a Gaussian. With this assumption, the width of the observed shower allows conclusions as to the location and density of the core for that dust trail encounter. However, we believe that a similar profile in these two dimensions is unlikely. The smaller the value of $r_E - r_D$, the greater the influence of particles ejected around perihelion, given that the node is placed very close to the comet's perihelion. For larger $r_E - r_D$, there may be no contribution whatsoever from particles ejected close to perihelion (see Section 3). Thus, the distribution of particles encountered at different $r_E - r_D$ will be a function of true anomaly and velocity of ejection, with the number of particles having the required velocity also being a function of the mass distribution of the ejected particles. For these reasons it is clear that more distant encounters will have a wider ZHR profile, even if no aging effect acts to diffuse the dust trails.

An attempt was made to make a generalized fit of activity width to several stream parameters, incorporating an aging effect. As noted above, the stream cross-sectional density decreases by a factor of $1/1.38 = 0.72$ per revolution. If this were due to an equal diffusion in both the heliocentric radial distance and the out of orbital plane dimensions, then, on each axis, one would expect diffusion to increase the width by $1.38^{0.5} = 1.17$. It is not clear what the ratio of spreading would be in these two axes, but determination of this ratio will have important implications for the nature of the dispersive effects. Despite an initial failure to make a generalized fit to stream width, there appear to be sufficient historical data, in the region of Δa_0, $r_E - r_D$ phase space where the major dust trail encounters of 2001 appear, to make an empirical determination of these stream widths. Thus, normalizing stream widths by 1.17^{n-1}, we derive an equivalent 1-rev ZHR FWHM of 32 minutes in 1966, 37 minutes in 1999, and 37 minutes in 1866. Then, interpolating from these and applying the width aging, we derive the following FWHM for the 2001 trails: 4-rev; about 70 minutes, 7-rev; 90 minutes, 9-rev; 130 minutes. The observed FWHM from the activity curve is dependent on the spreading out of the orbital plane. Should all the spreading occur in the heliocentric radial direction then the stream widths would be much closer to each other, based on the historical data, and all be of the order of 60 minutes. It is however most probable that stretching with age does occur out of the orbital plane and that the additional data from 2001 will help define the nature of the non-gravitational effects. It must also be stated that this model is very simplistic and ignores, for example, the likelihood of increased spreading of smaller masses. Another underlying assumption in all models considered by all authors is that splitting of particles after ejection is not a significant effect.

Given the limitations stated above, we still feel confident that our original double Gaussian fit with the addition of an aging factor gives an adequate representation of the storm region of dust trails. In 2001, we can expect a strong shower visible from North America and a guaranteed storm in East Asia.

3. The dust trail radiant signature

A consequence of the existence of multiple dust trails is that each trail will produce a slightly different radiant. The ejection velocities required for an Earth encounter at a specific time, and the subsequent orbital evolution of the particles, result in slight differences in direction and velocity at encounter. Conventional observing techniques may not be adequate to distinguish these differences, and the existence of "background" Leonids serves to further mask their existence. The velocity differences are small, of the order of 40 m/s in 2001, and no current observing technique could reliably distinguish such a difference. However, the difference between the mean radiant of one dust trail and another can be several arc minutes, a level quite adequate for longer focal length instruments.

The procedure to derive the dust trail radiant is similar to the original dust trail calculation referred to in Section 2 above as the "idealized model." This original calculation used ejection at perihelion (mean anomaly of zero) and an iterative process to find the required orbital period difference placing the dust at its node at the same instant the Earth lies at that nodal longitude. This defines a reference point on the dust trail from which subsequent calculations can be made. In the current calculations, we start at a variety of mean anomalies rather than just perihelion, and have as the end point a collision with the Earth's center at some specified time. This requires an iterative procedure including an additional factor, that of ejection direction, i.e., the procedure determines all three components of ejection velocity. Owing to non-linear behavior when integrating particles to the close proximity of a point-like Earth mass, integrations were terminated 0.1 days *before* a passage close to the Earth's center of mass, well within the Earth's radius, was indicated. Particles of interest were then integrated excluding the Earth's gravity, forward 0.098 days to a point closer to the Earth. The zenithal attraction caused by the Earth's gravity is considered separately (see Table 2, later) and is not accounted for in Figures 1–4.

The velocity vector representing the Leonid particle was then combined with the Earth's velocity vector (i.e., excluding diurnal aberration, which is also calculated separately and added to zenithal attraction to give the results in Table 2 later) at the collision time to give the geocentric radiant. Various tests including and excluding the gravity of the Earth-Moon system confirm that this procedure is valid. An assumption that we have not checked is that all particles that were ejected at a single mean anomaly and are on course to impact the Earth at a single instant

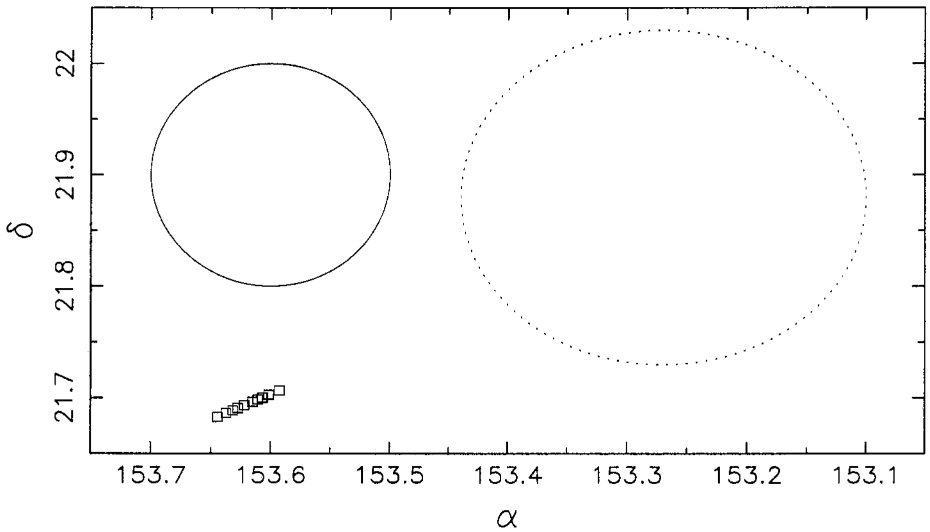

Figure 1 – Geocentric radiant structure of 3-rev trail (geocentric $v_g \approx 70.65$ km/s; α, δ in J2000.0) at November 18.1 UT, 1999. Radiants determined observationally by Betlem (28 photographic double station meteors) and by Rendtel et al. (over 1100 video Leonids) [8], and their estimated uncertainty, are shown as dotted and solid outlines. Our calculation has been done at a solar longitude differing by about 0°.02 from that used in [8], but this is small compared to the observational uncertainty.

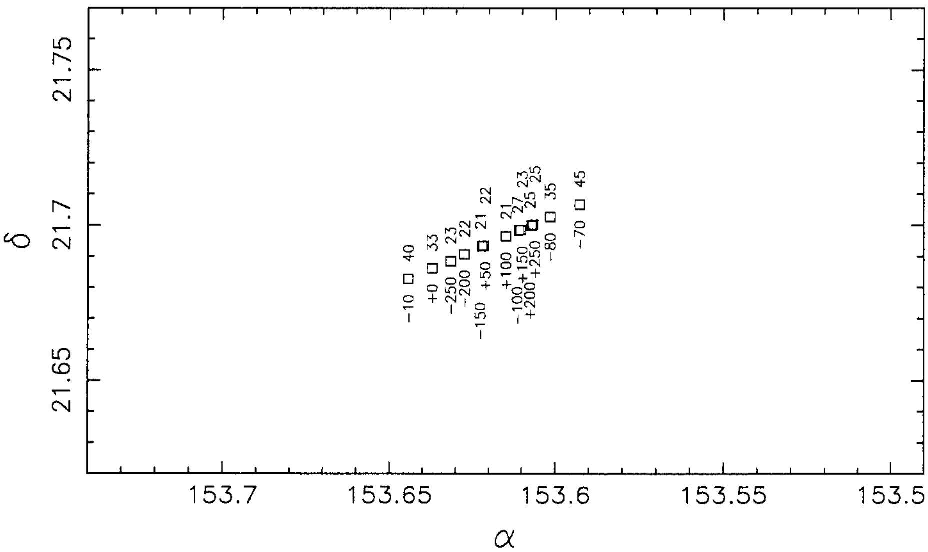

Figure 2 – Geocentric radiant structure of 3-rev trail at November 18.1 UT, 1999, i.e., as Figure 1, but enlarged so as to be on same scale as Figures 3 and 4. Each point is labeled firstly by the ejection time in days relative to the 1899 perihelion (±250 days corresponds to a heliocentric distance around 3.4 AU) and secondly by the magnitude in m/s of the unique 3-dimensional ejection velocity vector that allows a particle with radiation pressure parameter $\beta = 0.001$ to reach the desired Earth-impacting point at November 18.1 UT, 1999.

are moving on parallel paths as they approach, even if separated by approximately 10^4 km in space. This assumption is inherent in most considerations of radiants, and, even if it were to introduce a small error in the radiant position, the relative positions for the two dust trail encounters in 2001, and the internal radiant structure of these two dust trails, should be accurate.

The effect of solar radiation pressure on these results is insignificant, amounting to only about 0°.001 in the radiant position for a radiation pressure parameter $\beta = 0.001$ expected for visual Leonids. We have, therefore, not shown this in Figures 1–4. Any observed structure will result

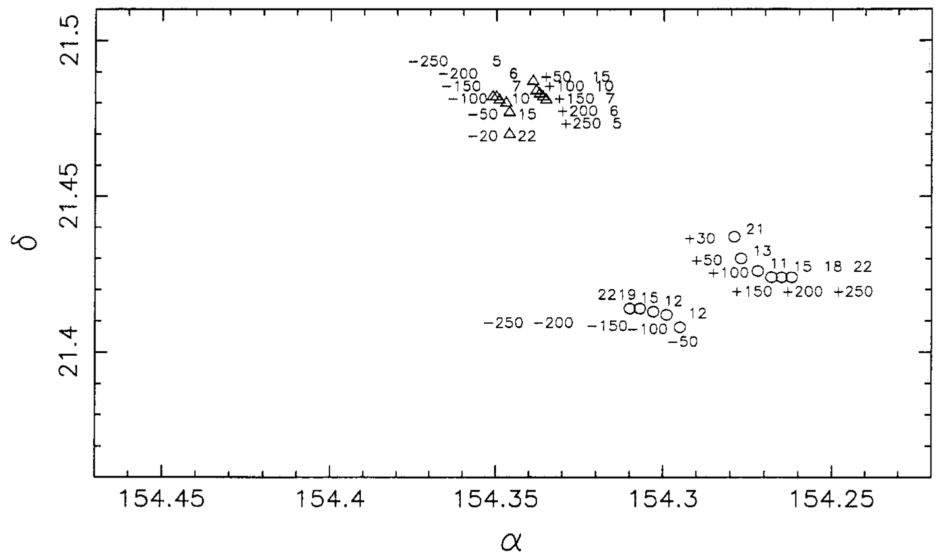

Figure 3 – Geocentric radiant structure of 4-rev (circles, $v_g \approx 70.69$ km/s) and 9-rev (triangles, $v_\infty \approx 70.65$ km/s) trails at November 18.7 UT, 2001. (Labeling explained in caption of Figure 2.)

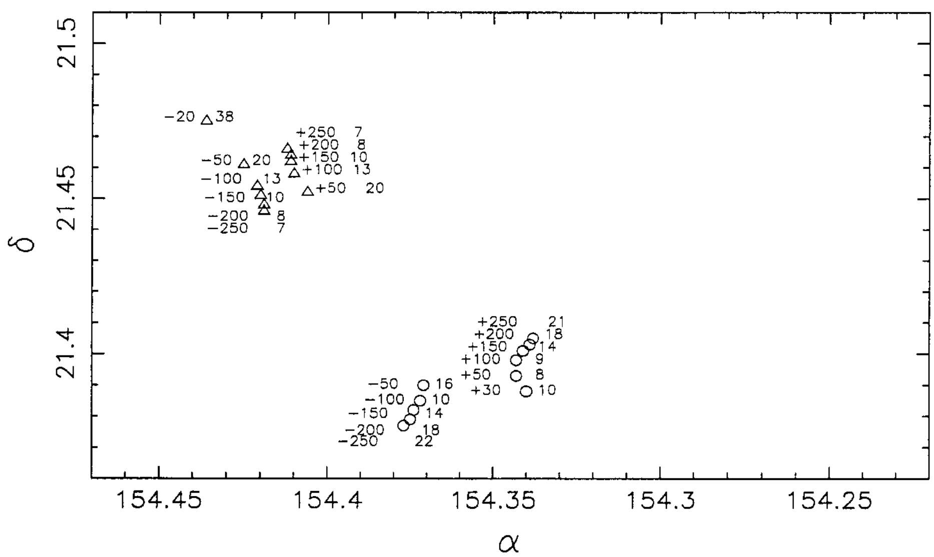

Figure 4 – Geocentric radiant structure of 4-rev (circles, $v_g \approx 70.69$ km/s) and 9-rev (triangles, $v_g \approx 70.65$ km/s) trails at November 18.8 UT, 2001. (Labeling explained in caption of Figure 2.)

from the ejection processes mentioned above, coupled with any other non-gravitational effects. The value of β does affect the tangential velocity that is required at ejection in order that the Earth impact is produced at the later date, although the other two components of ejection velocity are fairly insensitive to β. In Figures, 2–4 we have shown the magnitude of the ejection velocity in m/s, for β=0.001, as this is relevant if one is investigating ejection processes from the cometary nucleus. We have not listed the three ejection velocity components separately, but we mention that closer inspection of our results shows that for ejection within ±250 days of the 1899 perihelion passage, no impact solution in November 1999 exists with an ejection speed much below 20 m/s, for any reasonable (visual Leonid) β. That is, although β can be adjusted to reduce the required tangential ejection velocity, a significant component at right angles to this is needed. The 1999 storm therefore proves that ejection speeds above about 20 m/s exist, in a model where gravity and radiation pressure are the most important forces acting on meteoroids. Impact solutions in 2001 exist for very low ejection speeds, although, of course, the occurrence of the trail encounters this year will not preclude the existence of speeds above 20 m/s also.

Demonstrating the existence of dust trails through such a technique is hardly of consequence, as there is no doubt as to their reality. The aspects of importance are in the relative levels of activity from each dust trail radiant (as there will be overlapping activity in 2001), and in the internal structure of each radiant, something that could conceivably be used to investigate the activity of the cometary nucleus and ejection processes. Figures 3 and 4 give the radiant positions at two respective times during the 2001 encounters with the 4-rev and 9-rev trails. Other than the positional difference of the two dust trail radiants, there is evidently structure present within each trail. This structure results from the ejection of dust at different mean anomalies requiring different ejection speeds and directions to produce an Earth intersection at the specified future time. The resulting structure is of a curved line with each position representing a specific mean anomaly and ejection velocity from the specific cometary apparition. In both the 4-rev and 9-rev trails, there is a "zone of avoidance" towards the center of what can be called the dust trail radiant "signature." This region is a void if dust ejected from 55P/Tempel-Tuttle around its descending node, after consideration of subsequent orbital evolution, is sufficiently distant from the Earth's orbit that unrealistically large ejection velocities are required to produce the later Earth encounter. Therefore, no Leonids will be seen to come from that region. Thus, for each trail in Figures 3 and 4, the zone of avoidance splits the radiant structure into two parts that approximately correspond to ejection before and after perihelion, although this separation does not appear with the 3-rev trail in 1999 (Figures 1 and 2).

During the 1999 Leonid storm, a quasi-periodic variation in visual and video Leonid rates was detected [9,10]. A plausible mechanism for this was non-isotropic ejection from a rotating nucleus [9]. Reference [11] reported no evidence of these quasi-periodic variations from airborne video data. The probable explanation for this is that their video cameras were pointing low to the horizon and covering a substantial region of the meteor layer. This would require a correction of a few minutes between different meteors or small scale temporal variations could become hidden. Although the topocentric time correction is nominally defined as the observer's location, it should strictly be applied to the location of every meteor. In normal ground-based observation, this is mostly of little consequence, but, where the meteors are very distant from the observation location or they cover a large region of the meteor layer, a stricter use of the correction is required. A periodic variation might exist because particles ejected at different times (mean anomalies) show structure in the nodal longitudes, and so the Earth would pass through "waves" of particles at regular intervals. With only a single active area on the nucleus, this would be a very obvious effect, but multiple active areas would produce a quasi-periodic variability. As we have shown above that ejection at different mean anomalies produce a curved radiant signature, greater numbers of particles ejected at a specific mean anomaly should appear as a region of greater activity on the radiant signature. It may be possible to discern any quasi-periodic activity as a pattern of higher activity regions within the radiant signature. This could then be used to determine the rotation of the nucleus. The effect of particle ejection from active areas will vary between cometary apparitions and depend on the precessional state of the nucleus. Not every apparition need demonstrate this periodicity, but, as it appears to have been present in material ejected around the 1899 July perihelion passage, future encounters with the dust trail from this year should also show the effect. Diffusion with age will make this effect, when present, most marked in young dust trails, as diffusion will smear the peaks and troughs together.

Observers wishing to target the radiant exactly with narrow-field telescopes have to apply zenithal attraction and diurnal aberration to the geocentric velocity vector. This has been done for several locations listed in Table 2. As we have only recently developed our methodology for determining the geocentric radiant, we are not yet sure whether the small discrepancy between our calculations for 1999 and the observed position of the radiant in that year (Figure 1) indicates observational uncertainty or a systematic offset introduced by our methodology that should be applied to all our radiant calculations. However, the relative geometry of the radiant structure will be unaffected and the apparent positions in Table 2 represent the point on the 1866 dust trail at perihelion minus 50 days.

Table 2 – Apparent radiant corrected for zenithal attraction and diurnal aberration at various locations, at peak times of 9-rev and 4-rev trail encounters on November 18 UT, 2001. These values relate to the point in the 4-rev radiant signature resulting from ejection at perihelion minus 50 days. The same corrections would apply to other points in the radiant signatures.

Location	Time (UT)	α (J2000.0)	δ (J2000.0)	v_∞ km/s
Siding Spring	17^h13^m	154°17	+21°12	71.79
	18^h02^m	154°34	+21°10	71.75
Seoul	17^h24^m	154°05	+21°72	71.82
	18^h13^m	154°21	+21°65	71.79
Tokyo	17^h24^m	154°18	+21°65	71.80
	18^h13^m	154°33	+21°60	71.76
Xi'an	17^h25^m	153°98	+21°73	71.85
	18^h14^m	154°01	+21°72	71.84

The first time is the topocentrically corrected time for the predicted peak of the 9-rev trail and the second time for the peak of the 4-rev trail encounter on November 18, 2001. The geocentric position of this point in the radiant structure of the 4-rev trail at these times is $\alpha = 154°31$ and $\delta = +21°40$, respectively $\alpha = 154°33$ and $\delta = +21°39$. For other locations, the apparent radiant can be approximately interpolated from these positions. For time interpolations, the radiant motion can be approximately read off from a comparison of Figures 3 and 4, but for reference, the daily motions of the 4-rev and 9-rev trail radiants over the ~0.1 day around the Earth's encounter with them are $\Delta\alpha = +0°71$ and $\Delta\delta = -0°27$ (this is approximately the average motion, for the various points in those two dust trail radiants).

Observations are planned from Siding Spring Observatory to look at the 2001 Leonid radiant structure using telescopes of several meters focal length, sufficient to be certain of deriving radiants with an accuracy significantly better than one arc minute.

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Model of a One-Revolution Comet Dust Trail from Leonid Outburst Observations

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The dust trails of Comet 55P/Tempel-Tuttle lead to Leonid storms on Earth, threatening satellites in orbit. Here, I derive a model that accounts in detail for the observed properties of the dust trails evolved by the Comet at previous returns. It is based on the observed Leonid shower profiles and considers both peak intensity and width. The shower profiles and dust dispersions in the trail are interpreted as a projection of the Comet's light curve. Small trail shifts are observed that would put the 1767 dust trail closer to Earth's orbit in 2001 than thought before, increasing expected peak rates to a significant storm for North-American observers, between ZHRs of 3600 and 6900. Predictions for the 2002 storms are less affected. The trail shifts may result from directional ejection in a jet on a precessing comet nucleus. From the dust dispersion model, a mean particle density of 0.97 ± 0.13 g/cm^3 is calculated, semi-periods for the spin precession rate are found to be 270 ± 80 and 180 ± 20 years over the past 3 centuries, and the total dust mass loss during one return for 55P/Tempel-Tuttle is $(2.6 \pm 0.7) \times 10^{10}$ kg, which translates to an average dust to gas ratio of 2.4 ± 1.7.

1. Introduction

The debris of comets that is too large to be swept into the comet tail by radiation pressure does not scatter sunlight efficiently. The dust grains end up spread along the comet orbit in the form of a trail [1]. Dust trails are a natural consequence of the dispersion in the semi-major axis (Δa) of the orbits after ejection, causing some grains to make a wider orbit than others and return later. Recent Leonid storms are the result of Earth's crossing of the dust trails of parent comet 55P/Tempel-Tuttle. The dust trails from many past oppositions are recognized as individual meteor showers. The trails are narrow and often separated, because the orbit of the comet nucleus changes with each return to the Sun.

This important insight was gained only recently, when McNaught and Asher [2] and Lyytinen and Van Flandern [3], independently following similar work by Kondrat'eva and Reznikov [4], estimated the relative location of individual dust trails by calculating for each return the planetary perturbations on a single test particle that is ejected at perihelion with just the right difference in orbital period to end up near Earth at the time of a given shower. From year to year, the pattern of trails moves in and out of Earth's orbit, because planetary perturbations differ for particles that are at different positions along the comet orbit. From this, they identified the returns of 55P/Tempel-Tuttle that were responsible for the recent Leonid outbursts (Table 1).

Now, for the first time, meteor observations can provide insight about the comet mass loss and the dust dynamics that goes beyond information obtained from traditional mid-infrared observations of dust trails in the orbit of short period comets [1]. The showers sample the particle size distribution, measure cross-sections for a narrow range in mass, and are very sensitive to the effects of planetary perturbations. With the help of the dust trail positions calculated before, it is possible to map the dust distribution in a one-revolution dust trail based on both the width and the peak activity of the outbursts. I find that the observations point at small corrections to the calculations, but with significant implications for the predicted storm activity for North American observers and the peak time of the storm for Pacific observers in November 2001.

2. Prediction model

The relevant parameters of the model are explained in Figure 1. Each of these nine equations describes various aspects of the dust distribution.

The profile of the cross-section in Earth's path was measured accurately during the 1999 Leonid storm caused by an 1899 dust trail crossing. An airborne perspective [5] enabled us to measure simultaneously intrinsically faint meteors near the zenith and intrinsically bright meteors near the horizon. I find that the smaller grains peaked earlier in time and had a wider profile (Figure 2) [6].

$$\mathrm{ZHR} = \mathrm{ZHR}^{\max} \frac{(W/2)^2}{(\lambda_\odot - \lambda_\odot^{\max})^2 + (W/2)^2} \tag{1}$$

$$\mathrm{ZHR}^{\max} = \mathrm{ZHR}_o \times f_\mathrm{m} \times f(\Delta a) \times f(\Delta r) \tag{2}$$

$$W_\mathrm{E} = 2r \tan(W/2) \sin \varepsilon_\mathrm{h} \tag{3}$$

$$f(\Delta r) = 10^{-1450 \times |\Delta r + \delta r|} \tag{4}$$

$$\delta r = \Delta r^{\mathrm{obs}} - \Delta r^{\mathrm{cal}} = +0.00025 + 0.00020 \sin[2\pi(T - 1910)/270]\ \mathrm{AU} \tag{5}$$

$$W_\mathrm{E}(\Delta r) = 1.2 \times 10^{-4} \times 10^{-600 \times |\Delta r + \delta r|} \tag{6}$$

$$f(\Delta a) = \frac{(W_a/2)^2}{(\Delta a - 0.12 \pm 0.01)^2 + (W_a/2)^2} \tag{7}$$

$$s = 2.21 + 0.41 \log \Delta a\ (\mathrm{AU}) \tag{8}$$

$$\delta\lambda_\odot = \lambda_\odot^{\mathrm{obs}} - \lambda_\odot^{\mathrm{cal}} = -0.00010 + 0.00020 \sin[2\pi(T - 1910)/180] \tag{9}$$

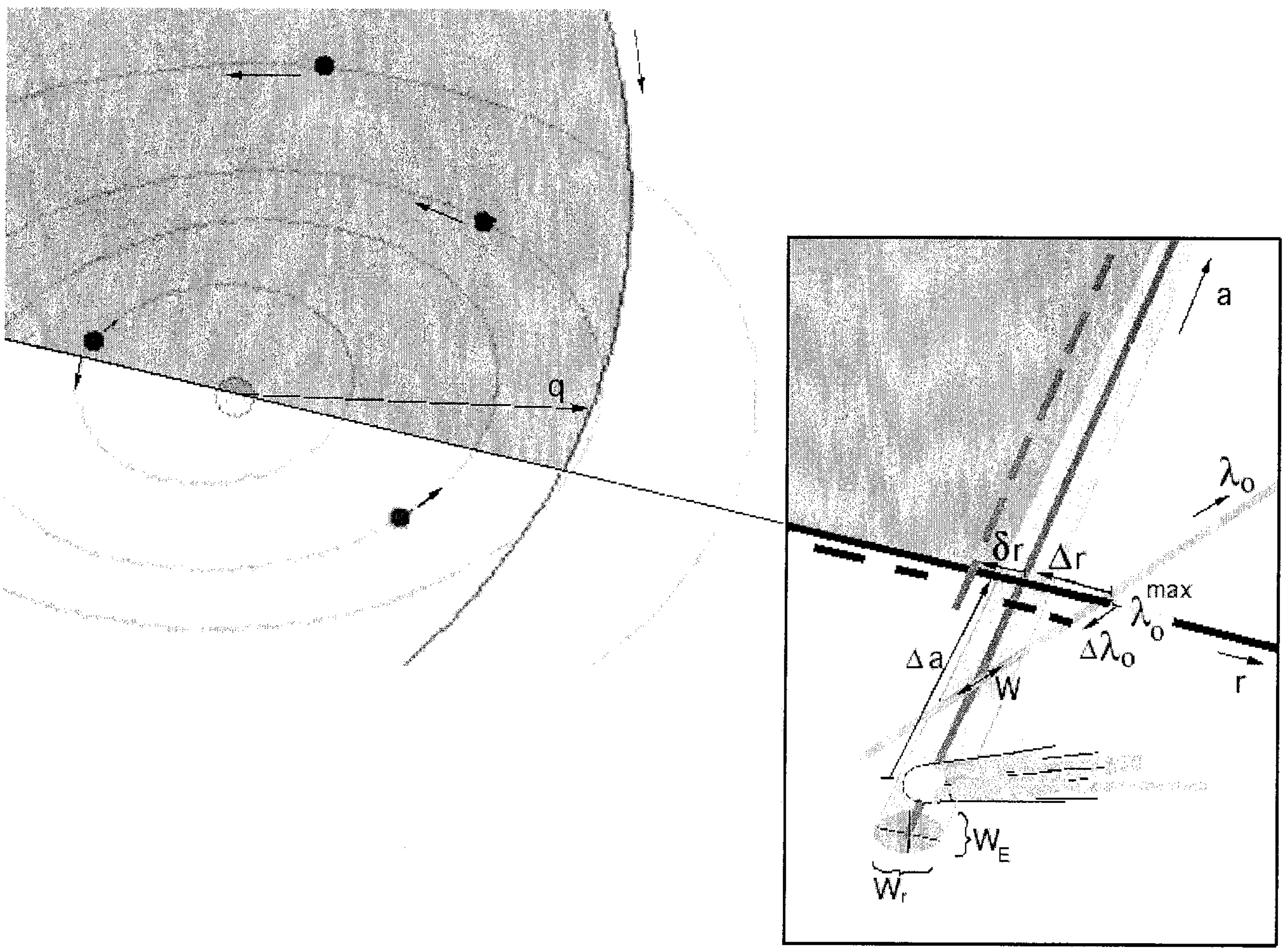

Figure 1 – Leonid shower prediction model. The diagram shows the orbit of 55P/Tempel-Tuttle and the definition of parameters used to describe the location and size of the dust trail in the prediction model; equations (1)–(9).

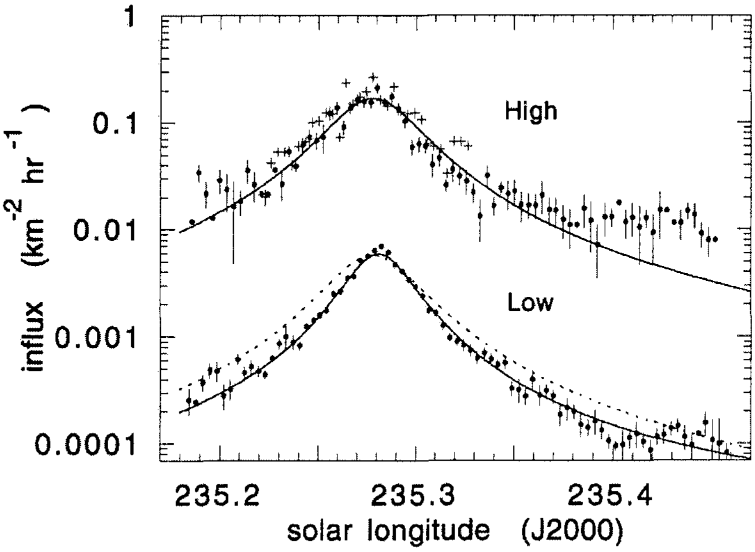

Figure 2 – 1999 Leonid storm influx profiles measured by cameras pointed at 37° (high) and 21° (low) elevation from the aircraft window. They represent masses of 5×10^{-4} g and 2×10^{-3} g, respectively. Data from the intensified high-definition TV camera at 90° elevation [28] are shown as crosses. To facilitate comparison, the dashed line copies the Lorentz curve fit for the high cameras to match the peak of the low cameras. The activity curves are scaled to match the cumulative influx up to the given mass that was representative of each set of observations. No smoothing applied. Error bars represent the statistical error from the number of meteors in each interval.

These cross-sections are well represented by a Lorentzian shape [7] as in equation (1) (Figure 1). The Zenithal Hourly Rate (ZHR) is a commonly used measure of number influx and is proportional to the rate of meteors observed by a visual observer under clear sky conditions and with the shower radiant in the zenith [8], W is the full-width at half maximum of the ZHR profile, while $\lambda_{\odot}^{\max}$ is the time of the peak in terms of solar longitude $\lambda_{\odot}$ (J2000.0), which is a measure of the Earth's position in its orbit. At the peak of the storm, the measured influx for meteoroids of visual magnitude brighter than +6.5 (2×10^{-5} g [9]) was 2.8 ± 0.4 meteoroids per square km and per hour [10]. This corresponds [8] to a ZHR of 4600 ± 700 ($\gamma = 1.0$, [8]) and an impact probability of 10% for the current satellite park as a whole (2670 satellites, 10 m^2 each, with solar panels mostly in edge-on position).

Smaller particles must have impacted in larger numbers, but did not result in satellite operation anomalies [11]. There is not a single power law over the whole mass range, as is normally assumed in dust trail models [1]. The mass power index $s = 1.64 \pm 0.05$ for meteoroids of mass less than 2×10^{-3} g (magnitude +0), while intrinsically fainter meteors have larger values, increasing to $s = 1.97 \pm 0.05$ for magnitude +6 meteors of mass 5×10^{-4} g [12]. Most of the mass is in the larger meteoroids. At least one fireball of 4 kg mass was observed from the *Leonid MAC*, while Leonids up to 5 kg are thought to have been responsible for impacts on the Moon during the crossing of the same dust trail [13]. The distribution of impact flashes with $s = 1.6 \pm 0.1$ suggests that the size distribution is not changed at least up to 5 kg. Integrating up to this mass, the peak influx corresponds to 0.070 g/km^{2}h.

Similar Lorentz-shaped profiles are found also from the mid-infrared brightness intensity across the dust trail of Comet 22P/Kopff [14]. The tail of the distribution has been interpreted as a separate dust component from grains of different size or morphology. However, the meteor shower shows no apparent change of the power law size distribution index across the Lorentz profile. I conclude that the tail of the distribution appears to be dynamically related to the peak and is not due to a separate dust component.

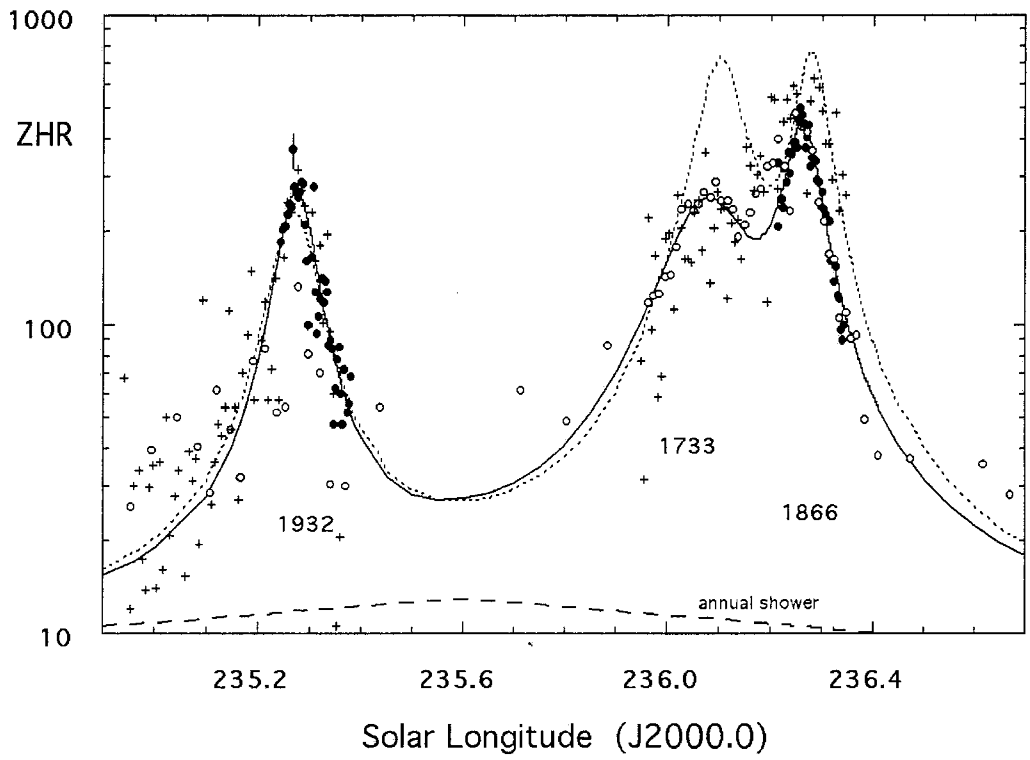

Figure 3 – Zenithal Hourly Rate curves for the 2000 encounters with the 1932, 1733, and 1866 dust trails. Black dots are results from intensified video cameras, while crosses are radio-MS data. Open circles are visual observations reported by Arlt and Gyssens [16]. The solid line is a fit of Lorentzian profiles. The broad dashed line is the level of annual shower activity in non-outburst years. The narrow dashed line shows the predicted rate by Lyytinen and Van Flandern [3].

Three further dust trail cross-sections were obtained in November 2000. The 1932 and 1866 dust trails were observed using the same intensified video cameras from a small Cessna aircraft over Florida, facilitated by Bo Gustafson of the University of Florida at Gainesville [15]. The 1733-dust trail peaked over Europe and was observed by Ilkka Yrjölä in Finland using radio forward meteor scatter to measure the meteor rate. In Figure 3, these results are compared to visual observations collected by the *International Meteor Organization* [16].

These cross-sections are at appropriate distances from the calculated trail centers to measure the dispersion of dust in the comet orbital plane perpendicular to Earth's orbit. Results of Lorentz profile fits are summarized in Table 1, which includes data from historic Leonid showers that originated from known trails. The values quoted are those in my original study [8], now normalized for a geometric dilution factor $\gamma = 1.0$, including the low 1966 peak rate. I see no reason to adjust this result. More recently published profiles are identical in shape to the low activity curve published in [8], and if the normalization is off by a factor of 10, it would disagree with all other observations of Leonid outbursts. A factor of 2–3 uncertainty in the absolute calibration for this particular data point would not significantly change the conclusions of this paper.

Each shower represents a cross-section at different Δa and Δr (Figure 1), and after a different number of revolutions N since epoch T. As recently pointed out by McNaught and Asher [2] and Lyytinen [3], the observed rate is a product of these three factors; see equation (2): a function $f(\Delta a)$ that describes the initial dispersion along the orbit in terms of semi-major axis, a function $f_{\rm m} \sim 1/N$ that describes the subsequent dispersion due to planetary perturbations and the number of revolutions (calculated from the relative distance between two nearby test particles), and a function $f(\Delta r)$ that describes the dispersion in the plane of the comet orbit in terms of radial heliocentric distance. ZHR_0 is the peak dust density in a one-revolution trail.

Table 1 – Dust trail parameters from past Leonid outbursts.

Year	N^*	Trail*	$f^*_{\rm m}$	Δa^*	Δr^*	$\delta r_{\rm obs}$	$W_{\rm obs}$	$W_{\rm cal}$	$\mathrm{ZHR}_{\rm obs}$	$\mathrm{ZHR}_{\rm cal}$	$s_{\rm obs}$
1999	3	1899	0.38	0.138	−0.00066	+0.00020	0.00063 ± 3	0.00073	4600 ± 700	4593	1.89
1998	3	1899	0.40	0.050	+0.00440	−0.0031	0.0024 ± 7	0.22	70 ± 20	0	1.64
1999	4	1866	0.50	0.118	+0.00160	+0.00003	0.0049 ± 15	0.0039	30 ± 15	109	1.83
2000	4	1866	0.13	0.114	+0.00077	−0.00013	0.0014 ± 2	0.0012	390 ± 20	459	1.76
2000	2	1932	0.55	0.300	−0.00120	+0.00028	0.0014 ± 2	0.0013	255 ± 20	312	1.99
2000	8	1733	0.27	0.064	+0.00076	+0.00039	0.0025 ± 6	0.0020	230 ± 20	216	1.77
1969	1	1932	0.95	0.934	−0.00004	+0.00037	0.00052 ± 9	0.00059	180 ± 20	192	2.19
1966	2	1899	0.52	0.168	−0.00013	+0.00028	0.00049 ± 5	0.00043	14000 ± 3000	17926	1.99
1867	1	1833	1.00	0.373	−0.00014	+0.00006	0.00042 ± 7	0.00043	4300 ± 900	4105	
1866	4	1733	0.37	0.059	−0.00029	+0.00051	0.00058 ± 11	0.00046	6800 ± 1100	9145	
1833	1	1799	0.95	0.174	−0.00021	+0.00021		0.00042	50000	31416	

* Calculations from [2,3].

For the first time, we have sufficient data to derive the last two functions iteratively by plotting the observed width and peak intensity ($\mathrm{ZHR}_{\rm o} \times f(\Delta r)$ and $f(\Delta a)$, respectively) as a function of Δr and Δa. Moreover, we can now also consider the stream width as a function of Δr and Δa. The measured width W needs to be corrected for the angle $\varepsilon_{\rm h} = 18.^\circ 1$ at which Earth crosses the trail; see equation (3). The result, $W_{\rm E}$, varies with Δr and is expected to be smallest at the trail center. The narrowest observed historic Leonid storms imply an intrinsic width of only $W^{\rm o}_{\rm E} = 0.00013 \pm 0.00001$ AU, or $(1.9 \pm 0.2) \times 10^4$ km.

Figure 4 shows the result. The variation with Δr of peak intensity (a) and stream width (b) is skewed towards negative values of Δr for both peak intensity and width, with comparatively narrower width and larger peak activity on the sunward side of the trail. The narrowest and strongest showers are detected when the trail position is calculated to be just outside of Earth's orbit. The observed trends do not comply with a cylindrical-symmetric Lorentz-profile dust distribution (dashed lines in (a) and (b)), and they are not Gaussian as assumed by McNaught and Asher [2].

For any given functional form, there are significant discrepancies. The large deviation for the 1998 encounter with the 1899 dust trail is understood from a perturbation by Earth in the previous return of 1965 [3]. I now measure a trail displacement of $\delta r = \Delta r^{\rm obs} - \Delta r^{\rm cal} = 0.0031$ AU from the calculated position. Other discrepancies are more puzzling. Especially, the 1733 and 1866 dust trail encounters in 2000, which occurred at the same calculated Δr, but resulted in significantly different peak intensity and width.

The agreement is not improved by assuming that the dust density falls off (and width increases) with the number of revolutions N^2 (or N) as assumed by Lyytinen and van Flandern [3], nor with initial Δa. The latter may sound surprising, because comet dust trails do show such a behavior [1,14]. However, unlike mid-infrared images of comet dust trails, the Leonid showers are always measured near perihelion.

One important clue is that the discrepancies in peak intensity and width deviate in sync. When the trails are too dense, they also tend to be too narrow. This argues against residual effects from significant variations in the comet activity along the orbit, or from one return to the next.

I postulate that the discrepancies are due to trail shifts δr (and $\delta\lambda_\odot$), possibly because of the particularities of comet dust grain ejection. McNaught and Asher [2] assume simply ejection at perihelion in the direction of comet motion, while Lyytinen and van Flandern [3] assume no ejection but high radiation pressure forces to arrive at the same initial Δa. However, note that the agreement in peak time and Δr calculated may be fortuitous because these assumptions lead to the same meteoroid orbit for given Δa.

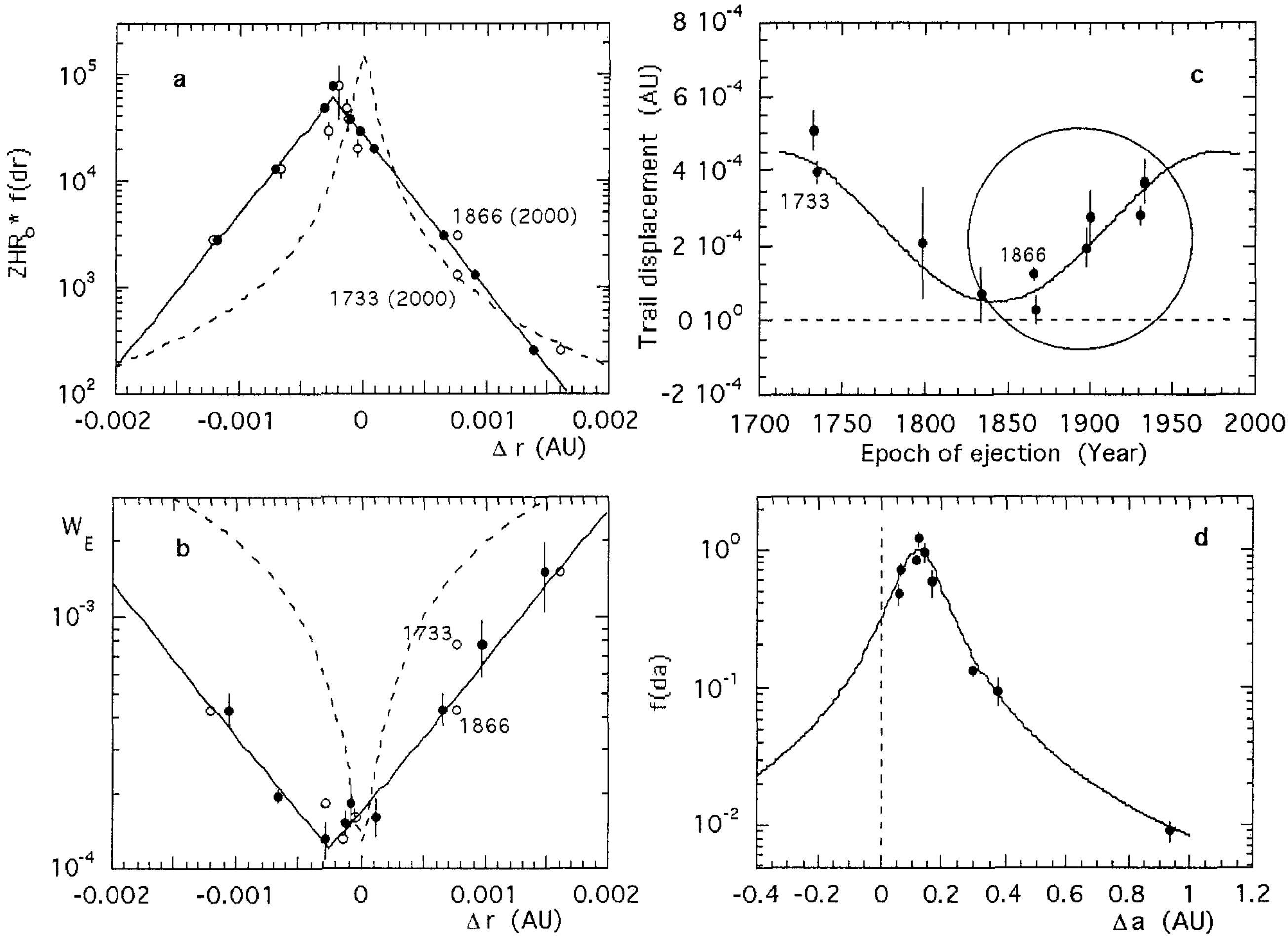

Figure 4 – (*a*) Trail cross-section along a radial direction to the Sun. Open symbols are observed values, dark symbols show values after correcting for trail shifts of (*c*). (*b*) As (*a*), for the variation of shower width with heliocentric distance. (*c*) Trail shifts that would fit the observed flux to a smooth exponential behavior (dark symbols in (*a*)). The open circle shows one trail equivalent width. (*d*) Variation of trail dust density with intrinsic semi-major axis dispersion (variation along the comet orbit) after correction for trail shifts in (*c*).

I find a smooth variation of shifts with epoch of ejection after matching a symmetric profile through the variation of peak intensity and width with Δr. The functional form that best describes the dispersion of dust in the heliocentric direction is equation (4) (solid line in Figure 4, (*a*)), with δr about +0.00025 AU. The equivalent width of this distribution (defined as integrated profile = width × peak rate) is $W_r^o = 0.00060 \pm 0.00006$ AU, or $(8.9 \pm 0.9) \times 10^4$ km, a factor of three larger than the equivalent width of $1.57 \times W_E^o = 0.00020 \pm 0.00002$ AU in the perpendicular direction.

The discrepancies from this relation are of similar magnitude and sign for ejections dating from the same epoch. There is a sinusoidal variation (equation (5)) as a function of the year of epoch for T going from 1733 until 1932 (solid line in Figure 4, (*c*)). The 1733 and 1866 trails represent the maximum and minimum of the functional trend, thus explaining the relatively large differences in shower width and intensity, despite similar $\Delta r^{\rm cal}$.

After correcting with equation (5), I find that the variation of width is also described well by an exponential curve (equation (6)), with about half the scale length. With this definition of $f(\Delta r)$ (equations (4) and (5)), I can plot the corrected peak rate as a function of the initial dispersion in semi-major axis to find a Lorentzian shaped $f(\Delta a)$ as expressed in equation (7), with $W_a = 0.16 \pm 0.02$ AU and $\mathrm{ZHR_o} = (6 \pm 1) \times 10^4$. This function represents the dispersion of dust along a one-revolution dust trail of comet 55P/Tempel-Tuttle. Note that W_a does not measure a physical distance, but, rather, a dispersion in semi-major axis.

The offset in the peak of the curve is an expected result from radiation pressure effects on the grains, and should be larger for smaller meteoroids. Indeed, among the most certain data, there may be a logarithmic increase (equation (8)) of the mass power index (s) with Δa away from the comet position (centered on magnitude +3.5 meteors).

Trail shifts are also expected to affect the time of the peak. The peak times calculated [2,3] differ from the observed peak times by up to ±16 minutes, which translated into astronomical units is of the same range as in equation (5). Six of eight data points are fitted by equation (9). This completes the formalism for predicting future Leonid returns as presented in equations (1)–(9). Results are in Table 2.

Table 2 – Forecast for the 2001 and 2002 encounters. The column labeled "•" indicates the major events.

N	Year	$\lambda_{\odot}^{max}$ (J2000)	Time (UT)	W (AU)	FWHM	ZHR^{max}	s	Lyytinen [3]	Asher [2]	Brown [17]	Time [2,3]	•
November 17, 2001												
1	(1965)	235.°24	13^h14^m	0.017		0	2.16			0		
2	(1932)	235.°37	16^h20^m	0.030		0	2.04			0		
3	(1899)	235.°54	20^h22^m			0	1.97			0		
November 18, 2001												
8	(1733)	236.°12	10^h10^m			0	1.71			0		
7	(1767)	236.°119	10^h09^m	0.00047	0.ʰ66	4200	1.76	2000	2500?	390	09^h58^m	•
6	(1800)	236.°202	12^h07^m	0.0030	4.ʰ25	40	1.76	110		600	12^h00^m	
5	(1833)	236.°279	13^h57^m	0.0049	6.ʰ80	14	1.79	60		390	14^h10^m	
10	(1667)	236.°408	17^h01^m	0.00147	2.ʰ05	170	1.59	600		170	17^h22^m	
11	(1633)	236.°422	17^h21^m	0.00091	1.ʰ26	510	1.56	260		150	17^h55^m	
9	(1699)	236.°413	17^h08^m	0.00088	1.ʰ23	1800	1.64	2000	9000	210	17^h31^m	•
4	(1866)	236.°446	17^h55^m	0.00058	0.ʰ81	2700	1.86	6100	15000	190	18^h22^m	•
November 17, 2002												
1	(1965)	235.°29	20^h35^m	0.0060		0	2.19					
November 18, 2002												
2	(1932)					0	2.07					
3	(1899)	235.°75	07^h31^m			0	2.00					
November 19, 2002												
7	(1767)	236.°615	04^h07^m	0.00047	0.ʰ65	4900	1.82	4500	15000		04^h02^m	•
6	(1800)	236.°710	06^h23^m	0.0028	3.ʰ96	58	1.83				06^h23^m	
5	(1833)	236.°709	06^h22^m	0.0032	4.ʰ49	41	1.83	160			06^h45^m	
4	(1866)	236.°871	10^h13^m	0.00040	0.ʰ56	5700	1.90	7400	30000		10^h44^m	•
November 19, 2006												
2	(1932)	236.°620	04^h53^m	0.00055	0.77	120	2.20	50	100		04^h48^m	
November 18, 2007												
2	(1932)	236.°109	22^h51^m	0.00042	0.58	200	2.22	30			22^h55^m	

3. Implications

Several dust trails are near Earth's orbit in November of 2001 and 2002 (Table 2). Our results argue against the large dispersion and trail shifts that follow from numerical models by Brown and by Göckel and Jehn [17]. Compared to the predictions by McNaught and Asher [2] and

Lyytinen and Van Flandern [3], our trail shifts increase the importance of the 1767 dust trail encounter relative to that of 1866. The 1767 dust trail is now expected to give the highest peak rate for Earth-based observers, an estimated $\mathrm{ZHR}^{\max} = 4200$. Different solutions for δr introduce an uncertainty over the range 3000–6900. The 1866 dust trail will contribute only in the range 2000–3500 and the 1699 dust trail in the range 1300–2500. However, the latter storms are slightly wider and both will merge into a single profile with a total fluence 1.6 times higher. Earlier estimates [2,3] had this peak 4–10 times more intense. The meteors will be somewhat brighter on average than during the storm of 1999. Other strong showers are predicted for 2002, but a Full Moon will illuminate this next encounter and the meteors will be fainter on average. No further storms are predicted until the return of 2099.

The observed trail shifts (about 0.00025 AU) are of the same order as the geostationary distance (0.00028 AU). In the anti-Sun direction, for example, the 1767 dust trail passage in 2001 causes an equivalent ZHR of 11000, or about 7 particles per square km and per hour with mass greater than 2×10^{-5} g at the peak. At the sunward position of a geostationary orbit, the 1866 and 1699 dust trails peak at 6800 and 4500, respectively.

The Moon is positioned at a relatively large distance of 0.00258 AU. In 2001, the most significant impacts will occur when passing the 1833 and 1800 dust trails (ZHRs of 2800 and 900, respectively), 2 hours after the Earth's passage by those trails at around 14^{h} and 16^{h} UT. This compares to a peak influx of about 1100 in 1999. Unfortunately, the Moon will be only 3 days old. In 2002, the trails will remain relatively far from the Moon.

4. Discussion

The shower profiles (Figures 1 and 3) can be understood as a projection of the Comet's light curve. Let us assume that the dust production rate is proportional to the water production rate. The light curve of Comet 55P/Tempel-Tuttle during the 1998 return is well described by [18] $m_r = 7.5 + 35 \log r$ (AU) (100 to 40 days before perihelion passage) and $m_r = 8.5 + 20 \log r$ (40 days before to 100 days after perihelion passage), with heliocentric magnitude $m_r = m_1 - 5 \log d$ (AU). Of all ejection, 90% occurs within 60 days from perihelion passage. Also, the water production rate of comets, as observed by OH radio line observations, correlates well with m_r, without invoking additional corrections to the OH line intensity or the visual magnitude: $\log Q_{\mathrm{H_2O}}(r)$ (mol/s) $= (30.74 \pm 0.02) - (0.240 \pm 0.03) m_r$ [19].

Most of the dust ejected at heliocentric distance r will end up near perihelion (where Earth encounters the stream) having dispersed away from the comet orbit to a distance Δx perpendicular to the comet orbital plane: $\Delta x = V_{\mathrm{ej}}^{\perp}(r) \times \Delta t(r)$. The function $\Delta t(r)$ is the time lapse from ejection until perihelion passage, and is readily derived from the comet ephemeris. By making the usual assumption that the ejection velocity is proportional to a power of the heliocentric distance, $Q(r)$ can be transformed into $Q(\Delta x)$ as a representation of the dust dispersion perpendicular to the orbital plane and, after correction for projection, in the path of the Earth.

The time-independent ZHR profile width can be understood because each particle, to first order, will return to its point of ejection after one return. Thus, the width measured near perihelion reflects the heliocentric dependence on ejection velocities and does not necessarily increase with orbital period.

The ejection velocities are determined by the width of the curve near the peak, while the tail of the Lorentz profile is sensitive to the adopted power law for the heliocentric distance dependence. To get particles far from the stream center as observed in the Lorentz wings of the ZHR profile, one has to invoke an increase of the ejection velocity with heliocentric distance. Within the range of comet activity, a perfect fit is provided to the intrinsic Lorentzian shape of the dust density in Earth's path (with $W_{\mathrm{E}} = 0.00013$ AU) for

$$\log V_{\mathrm{ej}}^{\perp}\ (\mathrm{m/s}) = (-0.22 \pm 0.05) - (0.19 \pm 0.03) \log M\ (\mathrm{g}) + (1.27 \pm 0.05) \log r\ (\mathrm{AU}). \quad (10)$$

The actual ejection velocity includes the comet's escape velocity, which is about 1.4 m/s for a comet radius R_c = 1.9 km [20]. Hence, $V_{ej}^{\perp}$ = 3.0 ± 0.3 m/s at perihelion for 3×10^{-4} g particles (magnitude +3.5). The reported mass dependence of ejection in equation (10) follows from the variation of width with mass (Figure 1). The model provides a natural explanation for the dispersion of particles in the profile and the implication is that the meteoroids in the ZHR profile tails were ejected at relatively large heliocentric distance.

In contrast, the measured ejection velocities are an order of magnitude smaller than predicted by the Whipple model for water vapor drag of cometary dust grains, modified to include adiabatic expansion, blackbody-limited nucleus temperature, and distributed production throughout the coma for ejection at perihelion, and specifically for particle density $\rho \approx 0.7$ g/cm^3 [22] and R_c = 1.9 km [21]:

$$\log V_{ej}\ (\mathrm{m/s}) = (1.05 \pm 0.33) - 0.167 \log M\ (\mathrm{g}) - 0.60 \log r\ (\mathrm{AU}). \tag{11}$$

The predicted speed for a 3×10^{-4} g meteoroid is V_{ej} = 44 m/s (within a factor of 2). The large tolerance reflects the various versions of equation (11) that are in use. If the dust ejection velocity is proportional to the gas ejection velocity as in equation (11), the result does not show the Lorentz wings in the observed ZHR curves.

One way to reconcile the Whipple model with the observations is to consider directional ejection from a dust jet and only the component of the mean ejection velocity vector perpendicular to the comet orbital plane. Indeed, one month prior to the 1998 perihelion passage of Comet 55P/Tempel-Tuttle, a dust jet was observed with an amplitude of 25° centered on a north-north-eastern direction [23]. The amplitude of the jet motion suggests a hot spot at +65° N, and a rotation period of 15.33 ± 0.02 hours [23].

The observed trail displacements (Figure 4, (*c*)) and the mass dependent shift in the node (Figure 1) can be understood as an effect of such jet. Ejection in a northerly direction explains the negative displacement in node. The torque exerted by the jet will cause a precession of the spin axis that can qualitatively account for the observed radial displacement δr with a semi-period of 270 ± 80 years (equation (5)), and in $\delta\lambda_\odot$ with a semi-period of 180 ± 20 years over the past 3 centuries (equation (9)), by changing the mean direction of ejection at perihelion in each return. With a nuclear axis ratio larger than 1.5 [20], this motion is not necessarily a simple sine law, hence the different semi-periodicities.

Directional ejection can account for the lack of a Lorentz wing in the observed $f(\Delta r)$. This is because the ejection vector in the comet orbital plane will be mostly in the direction of comet motion at large heliocentric distances, while nearly perpendicular to the comet motion vector at perihelion. The effect is to suppress the Lorentz wings. The three times higher dispersion implies that the ejection velocity at perihelion is $V_{ej} = 9.1 \pm 1.8$ m/s, still short of the Whipple speed (equation (11)).

Directional ejection has the opposite effect on the distribution of dust in the comet orbit $f(\Delta a)$. However, ejection in the direction of motion can not account for the full observed dispersion with Δa. Instead, a dispersion in perihelion distance δq does give the correct fall off away from the comet if Δq is related to a difference in semi-major axis (Δa) relative to that of the comet according to

$$\Delta a = -\frac{1}{1+e}\,\frac{GM(1-\beta)}{\frac{V_q^2}{2} - \frac{GM(1-\beta)}{q \pm \Delta q}} + \frac{1}{1+e}\,\frac{GM}{\frac{V_q^2}{2} - \frac{GM}{q}}, \tag{12}$$

where e is the orbit eccentricity: $q = a(1-e)$. A good fit to the data (solid line in Figure 4, (*d*)) follows by plotting $Q(\Delta x)$ versus $\langle \Delta a \rangle$, a mean of the two alternative possibilities of $\pm q$. For the Comet's velocity at perihelion V_q = 41600 m/s and q = 0.9766 AU, the variation in Figure 4, (*d*), is matched for $\Delta q = 6.2 \pm 0.7 \times \Delta x$ and $\beta = (7.0 \pm 0.6) \times 10^{-4}$. The model predicts the decay of dust density in front of the Comet, where no data are available.

The parameter β in equation (12) is the ratio of radiation over gravitational forces. While most of the observed dispersion is understood in terms of ejection velocities, the effect of radiation pressure is to shift the $f(\Delta a)$ profile to longer Δa due to an effective decrease of the gravitational potential. Unlike ejection velocities, the main effect will be along the Comet's orbit. The value derived from the observed shift of the peak Δa is valid for a visual magnitude +3.5 Leonid meteor of initial mass 3×10^{-4} g (equation (2)). From the common equation for β [24], I conclude that the average meteoroid density is $\rho = 0.97 \pm 0.13$ g/cm^3, if the radiation pressure coefficient $\langle Q_{\rm pr} \rangle = 1$ and the grains are spherical in shape. This compares well to the estimate of $\rho \approx 0.7$ g/cm^3 from the deceleration of a Leonid fireball [22].

To reconcile the observed ejection speed and its increase with heliocentric distance with the Whipple model, I postulate that larger grains fall apart in the comet coma and are the main source of the smaller grains. Such a scenario is not unlikely given that most of the mass is locked up in the larger grains. In that case, the ejection velocities of smaller grains reflect mostly those of the larger meteoroids, because gas drag is not efficient far from the nucleus surface. In order to explain the increasing speed with Δr, grains of given mass need to be derived from on average larger meteoroids closer to the Sun. Such an effect could occur because of increased thermal stresses on the grains. Indeed, the large grain mass distribution agrees with the value of $s = 1.53 \pm 0.1$ (reportedly valid over a wide 10^{-12} to 10^{-3} kg mass range) near the nucleus of Comet 1P/Halley and expected to reflect the dust distribution shortly after ejection [25]. The mass distribution for small grains is consistent with that expected for catastrophic fragmentation, where $\Delta N(M) \times M \approx M^{k/3}\Delta(\log M)$, with $k = 0.6$ for diameters smaller than one-tenth the diameter of the original mass [26]. Dust fragmentation in the comet coma is frequently implied to account for dust distributions and comet dust tail striae. Our meteor observations, too, show tentative evidence for spatial and temporal correlations that suggest breakup more than one return before Earth's encounter [27].

We now have all parameters in hand to calculate the total dust mass loss of 55P/Tempel-Tuttle during one return. That mass is proportional to the equivalent dimensions of the dust trail and the peak density. The trail dimensions are $W_r^{\rm o}$ by $1.57 \times W_{\rm E}^{\rm o}$ by $1.57 \times ((a + W_a)^{1.5} - a^{1.5})$ years. The peak dust density follows from $\mathrm{ZHR_o} = (6 \pm 1) \times 10^4$, while ZHR = 4600 corresponds to 0.070 g per square km and per hour, integrated up to $M = 5$ kg. From this, I calculate a total dust mass loss for each return of Comet 55P/Tempel-Tuttle of $(2.6 \pm 0.7) \times 10^{10}$ kg. From the observed visible magnitude light curve of Comet 55P/Tempel-Tuttle, I derive a total water production loss of $(1.1 \pm 0.7) \times 10^{10}$ kg. Hence, the ratio $M_{\rm dust}/M_{\rm gas} = 2.4 \pm 1.7$, in agreement with estimates from the infrared signatures of comet dust trails of short period comets [1,14]. I confirm that the loss of large dust grains dominates the mass loss of comets and demonstrate that meteor showers are a unique probe of this ejection process.

Acknowledgments

This work benefited greatly from discussions with Didier Despois and Esko Lyytinen, and a review by Kevind Zahnle. Part of this work was done while on a work visit at Bordeaux University, France. The deployment of the 1999 Leonid MAC mission was made possible by grants from the NASA Exobiology, Planetary Astronomy, Suborbital MITM, and Astrobiology Advanced Missions and Technologies programs, and by grants from NASA Ames Research Center and from the U.S. Air Force. The 2000 Leonid deployment was made possible by a grant from Data Grid Corporation. The author is supported by the Exobiology program.

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Ongoing Meteor Work

Ejection Velocities of Meteoroids from Comet Surfaces

Giovanni Imponente and Costantino Sigismondi

We present a model for the emission velocity of meteoritic material from a comet's surface, based on solar ablation, using fewer parameters than the well-established classical model by Fred Whipple. We also evaluate the binding energy of the meteoroids through a dimensional analysis equation. The role of the lithostatic pressure stored into the original comet's core is discussed for its relationship with cometary jets. Knowing the dynamical history of the meteoroids, the luminosity of the brightest meteors becomes an indicator of their ejection process. We propose tests for the 2001–2006 Leonid displays.

1. Introduction

A wide spread of meteoroid ejection velocities $v_{\rm ej}$ appears in the literature to explain the fireball shower that occurred as part of the 1998 Leonids display. Asher et al. [1] calculate $v_{\rm ej} = 2.4$ m/s and identify the 1333 perihelion passage as the main source of such meteoroids, while Arlt and Brown [2] consider also other years and velocities between roughly 10 and 50 m/s.

In [1], the kinematical conditions under which the meteoroids are injected into the resonant orbit have been studied regardless of their mass or their ejection process, while Arlt and Brown [2] have dealt with a wider spread of velocities arising from a wider spectrum in meteoroid masses. Despite the differences in the way in which meteoroid masses are treated, both papers follow the dynamical history of particles ejected during several orbits with respect to their encounters with the Earth in 1998.

Similar calculations by McNaught and Asher have appeared for the year 2000 [3]. Two different perihelia ejections (meteoroids 4 and 8 revolutions old) contributed to the peaks observed on November 18, 2000, with different initial kinematical conditions to enter the resonant zone. The velocity adopted in the model used in [3] has been $v_{\rm ej} = 25/r$ m/s, with r, the distance to the Sun, measured in AU, not considering differences in ejection velocities due to the meteoroids' masses.

We consider a model in which particles are emitted because of the Sun's ablation. This model permits to distinguish the origin of the meteoroids between cloud stripping [4], surface ablation [5], or jet emission. The discrimination is possible by comparing the luminosity of the brightest meteors with their kinematical constraints: the orbits of the brightest meteoroids are less affected by the radiation pressure.

Solar radiation is the fundamental energy source for meteoroid ejection from the cometary surface. We therefore have to consider material losses through ablation of the smallest grains which compose the exterior part of the comet.

According to Whipple [5], such grains have densities $\rho_s = 1$–4 g/cm^3, but Brown and Jones [6] consider the lower end of this range as unrealistic.

Following Verniani [7], who analyzed radio meteor data, the meteoroids detaching from the cometary surface have median densities ranging between $\rho = 0.2$–1.6 g/cm^3. Moreover, due to the fluffy structure of the comet parent body as a consequence of its evolution as a conglomerate of dusty grains, Rickman [8] gives as average density $\rho = 0.25$–0.80 g/cm^3. We will consider a density ranging between 0.2 and 2 g/cm^3.

Jets are observed in most comets, even with amateur equipment (when multiple nuclei appear as in the case of Comet C/1995 O1 (Hale-Bopp) [9], or without the occurrence of fragmentation, as in the case of C/1999 S4 (LINEAR) [10]), and they will be discussed in Section 3.

2. Solar radiation as source of kinetic energy

We evaluate the speed at which small iced particles (10^{-5} up to 10 grams) are ejected from a comet at perihelion. The solar radiation has to furnish energy to the particles to overcome gravitational and chemical bonds.

The solar constant at about 1 AU (the perihelion of the comet 55P/Tempel-Tuttle, the parent comet of the Leonids) is $E_\odot \approx 1300$ W/m^2, while the escape velocity is of the order of $v_{\rm esc} =$ 4 m/s for a comet mass $M \approx 10^{15}$ kg and radius 5 km (e.g., Halley's Comet) or $v_{\rm esc} = 1$ m/s (P/Tempel-Tuttle).

Through a dimensional method, we obtain an equation for the chemical binding energy per unit area $E_{\rm b}$ of an iced particle frozen onto the comet surface.

We have previously measured the breaking load ($M = 40 \pm 8$ kg) for a sample of ice, a regular cylinder with radius $R_{\rm c} = 2.5$ cm ($\pm 10\%$).

The relevant dimensions for the calculation of $E_{\rm b}$ are the mass M of the breaking load, the gravitational acceleration g (on Earth) and the area A of the surface where the break occurs. Energy per unit area, dimensionally, arises from the equation

$$[E][A]^{-1} = [M]^\alpha [g]^\beta [A]^\gamma \,, \tag{1}$$

which yields

$$E_{\rm b} = \frac{Mg}{\sqrt{A}} \,, \tag{2}$$

whence $E_{\rm b} = (8 \pm 2) \times 10^3$ J/m^2.

For other kinds of ice or conglomerates, with different chemical bonds, we can always apply the previous formula changing the values of the breaking load and the area, according to the experimental data. Ice binding energy can change from comet to comet, because of a different mix of the icy conglomerates with dust. The dust tail dimension could directly depend on that mix.

Grain detachment from the comet's surface requires the solar source of energy to act for a definite time interval, whose scale is evaluated by considering the time in which the solar constant $E_\odot$ provides the equivalent of $E_{\rm b}$:

$$\Delta t_{\rm det} = \frac{E_{\rm b}}{E_\odot} \approx 6 \text{ s} \,. \tag{3}$$

After detachment, the particle receives its kinetic energy, which determines its ejection velocity according to

$$\frac{1}{2} M_{\rm grain} {v_{\rm ej}}^2 = E_\odot \, \Delta t_{\rm ej} \, A_{\rm exp} \,, \tag{4}$$

where $M_{\rm grain}$ is the grain's mass, $\Delta t_{\rm ej}$ the time to acquire solar radiation as kinetic energy, and $A_{\rm exp}$ its area exposed to solar radiation. The grain is treated as a sphere of radius l embedded in the ice, so that $A_{\rm exp} = \pi l^2 \approx 3l^2$ and $M_{\rm grain} = \frac{4}{3}\pi\rho l^3 \approx 4\rho l^3$. We obtain

$$v_{\rm ej} = \sqrt{\frac{2E_\odot \, \Delta t_{\rm ej} \, 3l^2}{4\rho l^3}} = \sqrt{\frac{3E_\odot \, \Delta t_{\rm ej}}{2\rho l}} \tag{5}$$

which yields, depending of our choice of independent variables,

$$v_{\rm ej} = \frac{1.4\sqrt{\Delta t_{\rm ej}}}{\sqrt{l\rho}} = \frac{17.6\sqrt{\Delta t_{\rm ej}}}{{M_{\rm grain}}^{1/6} \rho^{1/3}} \,, \tag{6}$$

with ρ in g/cm^3, $v_{\rm ej}$ in m/s, l in meters, and $M_{\rm grain}$ in grams. Taking into account the escape velocity from the comet, the velocity of the meteoroid far from the comet is

$$v = v_{\rm ej} - v_{\rm esc} \,. \tag{7}$$

This value is used in the calculations for the variation δa_0 of the semi major axis a_0 [3].

To fix the parameter $\Delta t_{\rm ej}$, the duration of ejection, we consider the kinematical constraints on δa_0 [3] for the 2000 "American display" (November 18, $7^{\rm h}51^{\rm m}$ UT): $\delta a_0 = 0.11$ AU; and the FWHM of this parameter is 0.19 AU. The central value corresponds to an ejection velocity $v_{\rm ej} \approx \delta v + v_{\rm esc}$ with δv (corresponding to v in formula (7)) given by the formula

$$\frac{\delta a_0}{a_0} = \frac{2rv}{2GM_\odot - rv^2}\,\delta v\,, \tag{8}$$

with G the universal gravitation constant and $M_\odot = 2 \times 10^{30}$ kg the solar mass. For the perihelium passage of 55P/Tempel-Tuttle, $r = 1$ AU and $v = 42$ km/s, the orbital velocity of the Comet at perihelion, which yields

$$\frac{\delta a_0}{a_0} = 5.4 \times 10^{-3}\delta v\,. \tag{9}$$

Substituting $a_0 = 10.34$ AU, we find $v_{\rm ej} = 2.97$ m/s.

The brightest and most massive meteoroids are less influenced by the radiation pressure, and, therefore, we will take their velocity value from dynamical calculations [3]. The brightest meteors observed in the 2000 "American display" were of magnitude $m \approx -7$. We calculate their mass from the following relation between $M_{\rm grain}$ and the magnitude m [7]:

$$m = 40 - 2.5\log\left(2.732 \times 10^{10} \times M_{\rm grain}^{0.92} \times V_{\rm g}^{3.91}\right) = -4.0 - 2.3\log M_{\rm grain}\,, \tag{10}$$

with m in the range -6 to $+6.5$, $M_{\rm grain}$ in grams, and $V_{\rm g}$ the meteoroid's geocentric velocity in km/s (for the Leonids, 71 km/s). Therefore, for $m = -7$, $M_{\rm grain} = 20$ g; fixing also $\rho = 0.8$ g/cm^3 in equation (6), we obtain $\Delta t_{\rm ej} = 0.067$ s for $v_{\rm ej} = 2.97$ m/s.

When we substitute this value for $\Delta t_{\rm ej}$ in formula (6), we finally obtain

$$v_{\rm ej} = \frac{0.36}{\sqrt{l\rho}} = \frac{4.54}{{M_{\rm grain}}^{1/6}\rho^{1/3}}\,. \tag{11}$$

This relationship between $v_{\rm ej}$ and $M_{\rm grain}$ has been plotted in Figure 1, for different values of ρ. In Figure 2, the ejection velocity of the Leonid meteoroids is plotted versus their magnitude. Knowing the kinematical constraints for the nodal crossing, relation (11) can be used to predict the population index of the meteors.

3. Lithostatic pressure contribution as energy source

In this section, the role of the lithostatic pressure release on, or just below, the surface as the possible origin of the jets' engine is discussed.

Assuming for Halley-type comets 1000 periods as the life time in the inner regions of the solar system [11], a mass loss per orbital period of $\Delta M/M = 0.3\%$ [5] implies

$$\Delta R_{\rm com}/R_{\rm com} = 0.1\% \tag{12}$$

for each orbital period. Integrating relation (12) over the time spent by the comet in the inner regions of the Solar System results in

$$R_{\rm in} = R_{\rm com} \times e^{0.001\Delta p}\,, \tag{13}$$

where $R_{\rm in}$ and $R_{\rm com}$ are, respectively, the initial and present time comet's radii, and Δp is the number of expired orbital periods, say the number of passages at perihelium which are responsible for mass loss. In this estimate, assuming typical values for a comet $R_{\rm com} \approx 5$ km and $\Delta p = 1000$, we obtain

$$R_{\rm in} = 2.7 R_{\rm com} \approx 13.5 \text{ km}\,. \tag{14}$$

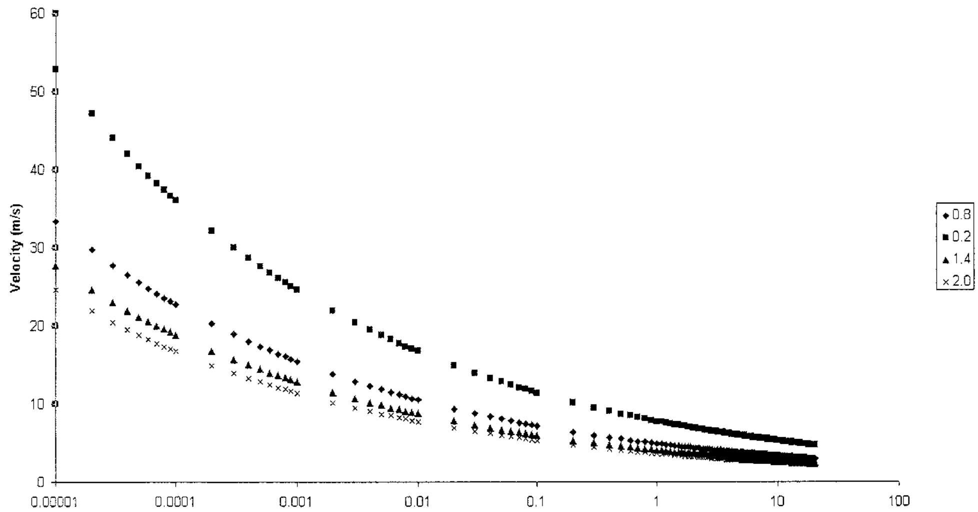

Figure 1 – Ejection velocity v_{ej} of the meteoroids versus their mass M_{grain} from 2×10^{-5} g up to 10 g. Note that we have adopted $v_{esc} = 1$ m/s, as in the case of the parent comet of the Leonid meteors. Four different values of ice density are considered: $\rho = 0.2$, $\rho = 0.8$, $\rho = 1.4$, and $\rho = 2.0$.

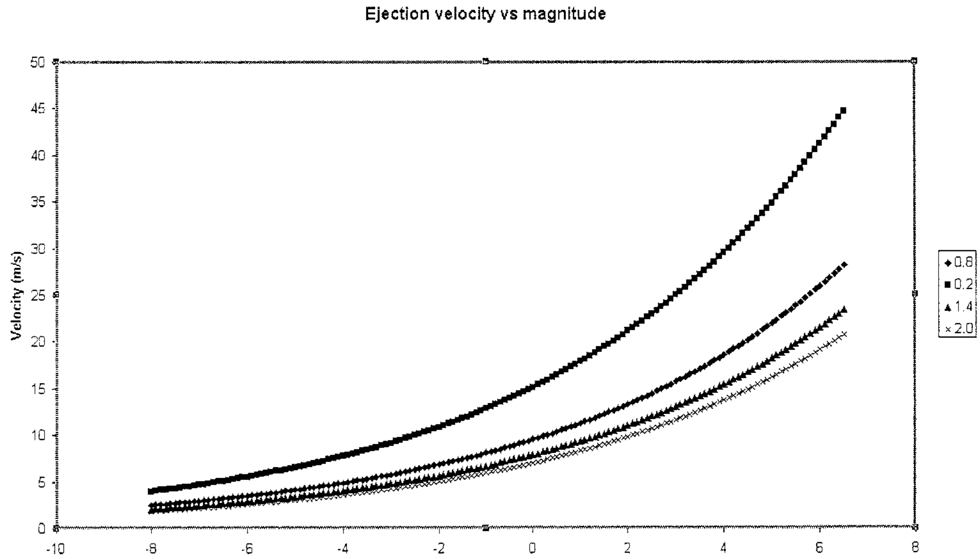

Figure 2 – Ejection velocity of the meteoroids versus their magnitude. Four different values of ice density are considered: $\rho = 0.2$, $\rho = 0.8$, $\rho = 1.4$, and $\rho = 2.0$.

The lithostatic pressure P is the one present at the time of formation at a given depth under the surface which is, in our case, about 13.5 km − 5 km = 8.5 km. The lithostatic pressure P was exercised by the original shell of material once existing from 5 to 13.5 km from the core, and is stored as internal energy of the material on its surface, following the equation

$$P = G\,\frac{4}{3}\pi\rho^2\,\frac{R_{\text{in}}^2 - R_{\text{com}}^2}{2}\,. \tag{15}$$

In our example, assuming $\rho \approx 0.8$ g/cm^3, we find $P = 12$ kPa.

Applying the gas-dynamics relation [12]

$$P = \frac{1}{3}\rho_g v^2 \qquad (16)$$

to the pressure (15) and to a "gas" of density $\rho_g = 1$ g/cm^3, the velocity obtained for this jet-like emission is

$$v_{jet} = \sqrt{\frac{3P}{\rho_g}} \approx 7 \text{ m/s}, \qquad (17)$$

enough to regard short-lived jets as the product of such inner energy stored into the comet's ice.

Although, in our model, we consider particles emitted through solar ablation, lithostatic pressure can explain how solar radiation detaches grains successfully.

4. Discussion and conclusions

The parameterization suggested here is in good agreement with Whipple's results in the same range of densities [5], though with a lower number of free parameters used.

Once the parameter Δt_{ej} is fixed, our formula is a good fit for the process, although it does not cover the physics completely. On the other hand, McNaught and Asher [3] adopted $v_{ej} = \frac{25}{r}$ m/s (see Section 1), but their model does not consider differences in ejection velocities due to the meteoroids' masses.

In our model, the balance between solar radiation power and ice binding energy cannot explain the observed long-lived jet structures of comets, as well as comet's mantle desegregation processes [13,14], which are probably responsible for the production of the heaviest ($\gg 20$ g) meteoroids. Jets can eject meteoroids of several grams weight, and we have discussed their relation to lithostatic pressure.

From the kinematical constraints [3], we can predict the brightest events expected for the upcoming Leonid displays in 2001, 2002, and 2006, using formulae (7), (9), and (11). These predictions are shown in Table 1.

Table 1 – Upper limits for the brightness of fireballs (i.e., lower limits for their magnitude) in the 2001–2006 Leonid displays. Dates and δa_0 are from [15] for 2001 and 2002, and for 2006; the assumed comet density is $\rho = 0.8$. The observations of 1999 [16] and 2000 [17] confirm the quality of the predictions made in [3,18]

Date and time (UT)	δa_0	v_{ej}	Magnitude
2001 Nov 18.413 (09^h55^m)	+0.085 AU	2.52 km/s	$m \geq -8.0$
2001 Nov 18.725 (17^h24^m)	+0.046 AU	1.82 km/s	$m \geq -9.9$
2001 Nov 18.759 (18^h13^m)	+0.146 AU	3.61 km/s	$m \geq -5.8$
2002 Nov 19.162 (03^h53^m)	+0.117 AU	3.10 km/s	$m \geq -6.7$
2002 Nov 19.437 (10^h29^m)	+0.177 AU	4.17 km/s	$m \geq -5.0$
2006 Nov 19.198 (04^h45^m)	+0.96 AU	18.2 km/s	$m \geq +3.9$

If some events will be recorded dramatically brighter than these predictions, even considering the FWHM of the parameter δa_0 in the calculation of the ejection velocity, only the hypothesis of a comet "dressed" by a cloud of large meteoroids which are accelerated by the solar radiation via sublimation [4] could explain their presence in the meteor shower. This verification will be particularly interesting in the case 2006, when rather faint meteors are expected.

Acknowledgments

Thanks are due to Professor Gian Carlo De Casa (University of Rome "La Sapienza") for the valuable discussions on lithostatic pressure.

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Dedication

To the memory of Mario Imponente († October 19, 2001).

2001 Perseid Fireball Observations

Martin Beech and Alison Illingworth

We present a set of fireball observations gathered by the *Southern Saskatchewan Fireball Array*. In total the all-sky, video camera systems captured 60 Perseid and 4 sporadic meteors with magnitudes less than −1 in the time intervals August 12.21 to 12.50 UT and August 13.21 to 13.50 UT. The hourly rate of Perseid fireballs peaked between 8^h00^m and 9^h00^m UT on August 12. We deduced a population index of $r = 2.18 \pm 0.40$ for the night of August 11-12, and $r = 1.90 \pm 0.38$ for the night of August 12-13. To a limiting magnitude of −5, we detected no Perseid meteor related VLF transients.

1. The SSFA

The *Southern Saskatchewan Fireball Array* (*SSFA*) consists of three all-sky, video camera systems located in the southernmost prairie region of Saskatchewan, Canada, at Regina, Moose Jaw, and Laird. The camera systems have been designed and supplied by *Sandia National Laboratories*, New Mexico, and each system consists of a 45 cm diameter spherical mirror combined with a centrally mounted, and downward looking video camera. The systems afford all-sky monitoring (except for local buildings and obstructions) and Figure 1 shows the panorama available to the Regina camera. The video image is recorded on to standard VHS videotape, and for the 2001 Perseid campaign all tapes were manually reviewed.

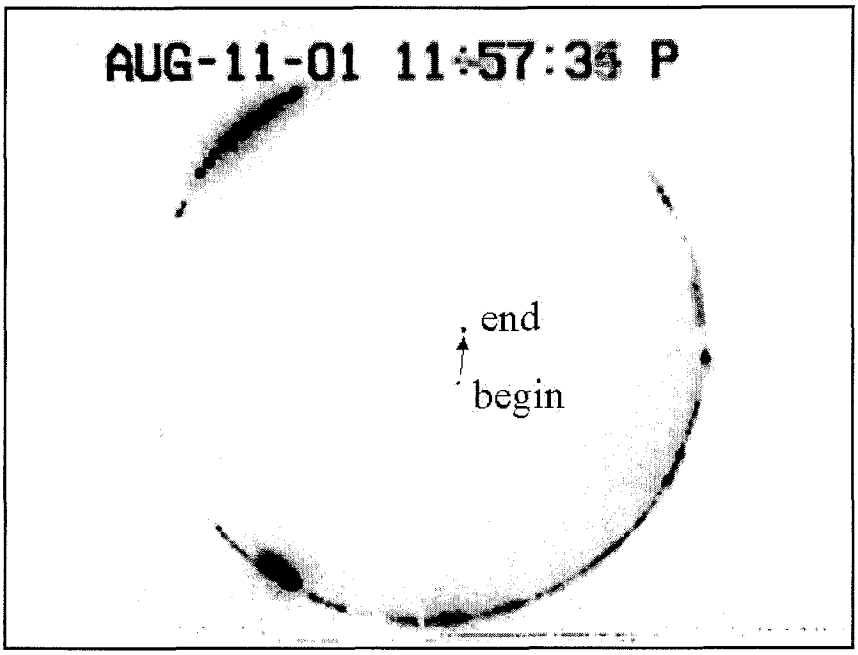

Figure 1 – Two superimposed, negative, video frames of a Perseid fireball captured by the all-sky video camera system at Regina (the local time is UT minus 7 hours). The fireball was one of the brightest detected by the camera system at Regina and had an estimated maximum visual magnitude of −3. The beginning and end positions are shown and the arrow indicates the direction of motion. The duration of the meteor was 25/30th of a second.

The limiting magnitude of the camera systems has been evaluated by planet image detection and through iridium flare observations. We found, for example, that during the nights of our Perseid observations both Mars (magnitude −1.5) and Jupiter (magnitude −2.0) were easily detected. Saturn (magnitude −0.3), however, was below the camera detection threshold. We also find that iridium flares down to magnitude −1 to −2 are routinely recorded. The system limiting magnitude is therefore taken to be magnitude −1.

2. Observations

In an unusual display of restraint (for Saskatchewan), the weather over the entire weekend of the 2001 Perseids was perfect. We had virtually no cloud interference and very little heat haze to deal with—also, and for a change, there was no high-level smoke pollution as a consequence of large forest fires. The hourly fireball counts for our 2001 Perseid campaign are given in Table 1. It can be seen that on the night of August 12 the hourly rate peaked between 8^h and 9^h UT at 8 fireballs brighter than magnitude −1 per hour. On August 13 the fireball rate was remarkable constant, from 7^h UT to 11^h UT, at about 5 fireballs brighter than magnitude −1 per hour. The spatial distribution of the fireballs recorded on the night of August 11-12 (and the four iridium flares visible during the observing interval) is shown in Figure 2. Many of the fireball detections appeared as transient point sources on the video image (corresponding to a few video frames). For these events we are simply catching either a terminal flare or the brief interval around maximum brightness (the train being at sub-detection brightness). The magnitude distribution of the observed Perseid fireballs is given in Table 2. Magnitudes are eye-estimates based upon comparisons with iridium flares, the planets, and the Moon. From the observed magnitude distribution we deduce a population index (from 35 meteors) of $r = 2.18 \pm 0.40$ for the night of August 11-12. Our observations from August 12-13 indicate (from 25 meteors) a population index of $r = 1.90 \pm 0.38$. While based upon small number statistics our derived population indices are consistent with the typical value quoted for the Perseid shower (i.e., $r = 2$).

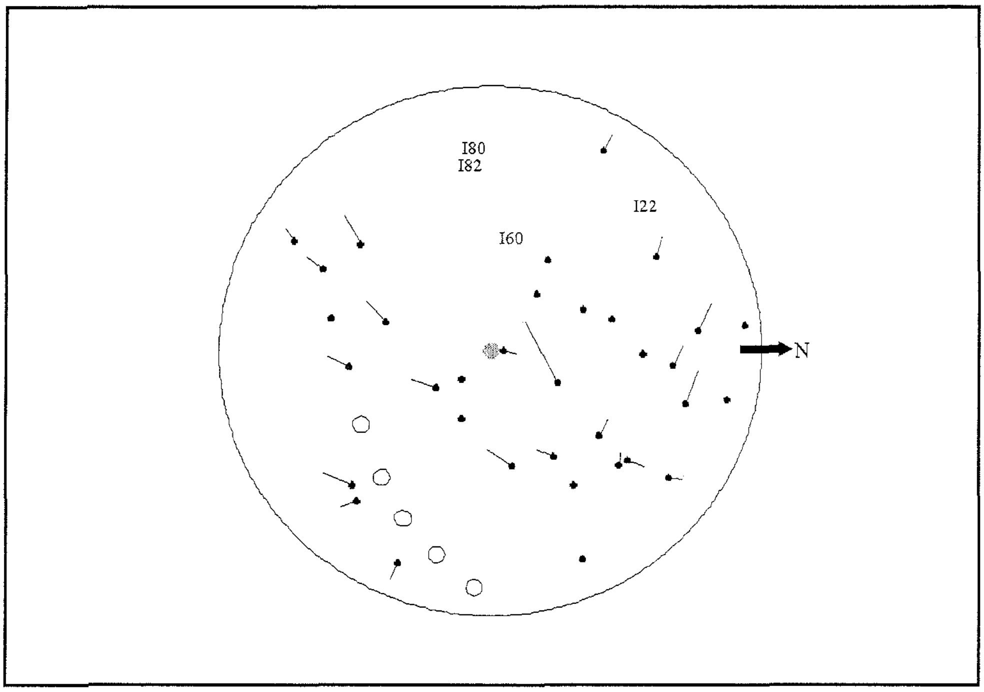

Figure 2 – Spatial distribution of Perseid fireballs detected on the night of August 11-12. The dots represent short duration events (t about a few 1/30ths of a second—i.e., several video frames). The dot and line symbols indicate the direction of sky motion for those Perseids exhibiting a recorded train. The shaded circle at the center of the figure represents the region of sky obscured by the camera housing. The non-filled circles correspond to the positions of the Moon at one-hour intervals starting at 8^h00^m UT. The outer circle is the horizon, and north is to the right in the diagram.

Brown and Rendtel [1] found that the population index for visual Perseid observations collected by the *IMO* between 1988 and 1994 varied from about 1.9 to about 2.2, so we find no obvious indication that the population index is changing at higher masses (i.e., brighter Perseids).

3. Discussion

Observations of iridium satellites and planets indicate that we can detect objects of apparent magnitude −1 down to altitudes of about 15° above the horizon. The surface area of sky monitored, to the cameras' limiting magnitude, is therefore some $A_{\rm sky} = 3.6 \times 105$ km^2 assuming a Perseid meteoroid ablation height of 100 km. We can use this "detection" area to estimate meteoroid fluxes via the relationship

$$\text{flux (meteoroids/m}^2\text{s)} = \frac{N}{3600 \times 10^6 \times A_{\rm sky}},$$

where N is the number of fireballs observed per hour. With an entry velocity of 60 km/s, a Perseid meteoroid of mass around 10^{-4} kg is required to produce a meteor of magnitude −1. From the deduced fireball counts (see Table 1), the flux of Perseid meteoroids of 10^{-4} kg and larger between 8^h and 9^h UT on August 12 (i.e., our peak rate) was about 6×10^{-15} per square meter and per second. This peak flux corresponds to a spatial number density of $S_{-1,\rm max} \approx 0.1$ meteoroids (with masses greater than 10^{-4} kg) per 10^9 km^3. Brown and Rendtel [1] deduce a spatial number density of $S_{6.5,\rm max} \approx 95$ meteoroids (with masses greater than 10^{-8} kg, i.e., Perseids brighter than magnitude +6.5) per 10^9 km^3. For a mass distribution index of $s = 1.75$ (corresponding to a population index of $r \approx 2.0$)[1], we would expect that $S_{-1,\rm max} \approx 10^{-3} \times S_{6.5,\rm max} \approx 0.096$. Our deduced spatial number density ($S_{-1,\rm max}$) is consistent,

[1] Recall that the population index and the stream mass index are related as $s = 1 + 2.5\log_{10}(r)$, and that the flux of meteoroids with masses greater than m is $f(m) \approx m^{(1-s)}$.

therefore, with expectation for a constant mass index. This result implies that we can be reasonably sure that the population index does not vary significantly for Perseid meteoroids over the entire mass range from 10^{-8} kg to about 10^{-1} kg (the latter mass corresponding to the brightest, magnitude −5, Perseid that we observed). If there is a change in the Perseid stream mass index, for large, meter-sized meteoroids, as discussed by Beech and Nikolova [2] with respect to electrophonic sounds being generated by Perseid meteors, then it must presumably come about for masses greater than several tenths of a kilogram. The implied near constant mass index suggests that the upper limit to the flux of meter-sized Perseid meteoroids is about 10^{-19} per square meter and per second.

Table 1 – Hourly number of observed Perseid fireballs.

Day (UT)	Time interval	Perseids (sporadics)	Day (UT)	Time interval	Perseids (sporadics)
August 12	05^h00^m–06^h00^m	4 (1)	August 13	05^h00^m–06^h00^m	0
	06^h00^m–07^h00^m	1		06^h00^m–07^h00^m	2
	07^h00^m–08^h00^m	6 (1)		07^h00^m–08^h00^m	6
	08^h00^m–09^h00^m	8		08^h00^m–09^h00^m	5 (1)
	09^h00^m–10^h00^m	7		09^h00^m–10^h00^m	5
	10^h00^m–11^h00^m	5		10^h00^m–11^h00^m	5 (1)
	11^h00^m–12^h00^m	4		11^h00^m–12^h00^m	2

Table 2 – Magnitude distribution of Perseid fireballs observed on the nights of August 11-12 and 12-13.

Magnitude	−5	−4	−3	−2	−1
August 11-12	1	2	3	10	19
August 12-13		2	5	6	12

We note briefly that concurrent to the video camera observations a very low frequency (VLF) radio wavelength monitoring experiment was in operation. We detected no simultaneous VLF transients at the times that fireballs were recorded. Given that the brightest fireball we detected had an estimated magnitude of −5, this negative result is at least consistent with our earlier observations [2,3] that a magnitude −10 or brighter fireball is required to produce VLF transients through the tangled "magnetic spaghetti" mechanism of Keay [4]. Likewise, no short duration VLF "bursters" were recorded. This negative "burster" result is also consistent with the ideas presented by Beech and Foschini [5], who suggest that a detonating, magnitude −8 meteor is required before the "space charge separation" mechanism can come into effect.

Acknowledgments

Martin Beech wishes to extend his gratitude to Dr. R. Spalding of *Sandia National Laboratories* for supplying the equipment used in this study. We also extend our gratitude to Ken Yanko, Mario Bevan, and Bill Voakes of *Campion College* for their invaluable help in installing the camera and equipment used in the *SSFA*.

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