The Leonids

Bulletin 17 of the International Leonid Watch First Global Analysis of the 2001 Leonid Storms

Rainer Arlt, Javor Kac, Vladimir Krumov, Andreas Buchmann, and Jan Verbert

Observers in America and Asia have monitored strong peaks of Leonid activity on November 18, 2001. We present a first analysis of global data based on the reports of 177 observers who recorded 137 146 Leonids. Main activity peaks are found for solar longitudes (all J2000.0) $\lambda_\odot = 236\overset{\circ}{.}137 \pm 0\overset{\circ}{.}003$ (November 18, $10^{\rm h}39^{\rm m} \pm 4^{\rm m}$) and $\lambda_\odot = 236\overset{\circ}{.}458 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}16^{\rm m} \pm 4^{\rm m}$). Secondary peaks are found near the main Asian maximum at $\lambda_\odot = 236\overset{\circ}{.}448 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}02^{\rm m} \pm 4^{\rm m}$) and $\lambda_\odot = 236\overset{\circ}{.}467 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}30^{\rm m} \pm 4^{\rm m}$). The American peak actually exhibits a bimodal structure with two similar maxima at $236\overset{\circ}{.}137 \pm 0\overset{\circ}{.}003$ and $236\overset{\circ}{.}154 \pm 0\overset{\circ}{.}003$, the second of them being 24 minutes later. The population index shows sharp peaks for the storms, whereas the background level during the interval $\lambda_\odot = 235\overset{\circ}{.}6$–$237\overset{\circ}{.}0$ is characterized by $r < 1.9$.

1. Overview of data and predictions

The theory of the dynamics of the Leonid meteoroid stream has seen an impressive advance during this epoch of the return of the parent comet, 55P/Tempel-Tuttle. We shortly recollect the latest predictions given before the 2001 Leonid peaks and will discuss them together with the observational results in Section 4. The model of Lyytinen et al. assumes that particles leaving the Comet suffer from solar radiation pressure which always increases the semi-major axes of orbits [1]. They predicted major peaks for $10^{\rm h}28^{\rm m}$ UT, $18^{\rm h}03^{\rm m}$ UT, and $18^{\rm h}20^{\rm m}$ UT on November 18. The dust originates from the perihelion passages in 1766 (7 revolutions ago), 1699 (9 revolutions ago), and 1866 (4 revolutions ago), respectively. The refined model of McNaught and Asher resulted in $9^{\rm h}55^{\rm m}$ UT, $17^{\rm h}24^{\rm m}$ UT, and $18^{\rm h}13^{\rm m}$ UT, respectively [2]. The approach of Brown and Cooke [3] may be described as a full stream model with a total of one million particles. Much broader structures result from the stream components suggesting a wide single maximum near $13^{\rm h}$ UT. The contributions from individual perihelion passages are centered near $10^{\rm h}$ (7 revolutions), $12^{\rm h}$ (6 revolutions), and $17^{\rm h}30^{\rm m}$ (4, 5, 9, 10, and 11 revolutions). The 6-revolution-old particles are not considered relevant in [1] and [2].

The process of entering observational data into the *Visual Meteor Database*, thus making them suitable for analysis of the visual activity of the Leonids, is not yet finished. The sample now contains the reports of 177 observers who recorded 137 146 Leonids from from 28 countries in America, the Pacific, Asia, Australia, Europe, and Africa. We have first added the high-resolution reports with details for one-minute or two-minute bins. Since we try to detect features with time differences of the order of 10 minutes, observing reports with 10-minute periods are not applicable. Also 5-minute periods are hardly acceptable, because the time correction for topocentric encounter (see Section 3) will shift observing periods by a few minutes, and the average profile is more "fuzzy" than a real 5-minute-bin profile. We would like to emphasize that *the analysis of meteor storms requires a fine breakdown of observing periods as well as of magnitude distributions* (see Section 5).

2. Population index analysis

The increase of meteor numbers with their magnitude is expressed by the population index r. We derived average values for r using the average magnitude difference to the limiting magnitude of many observers [4]. Most of the people recorded magnitudes despite the high number of Leonids, as recommended before the storms.

Figure 1 shows the full profile obtained by an adaptive-bin algorithm which tries to keep the number of meteors in each bin roughly constant. The magnification of this profile is shown in Figure 2.

2001JIMO...29..187A

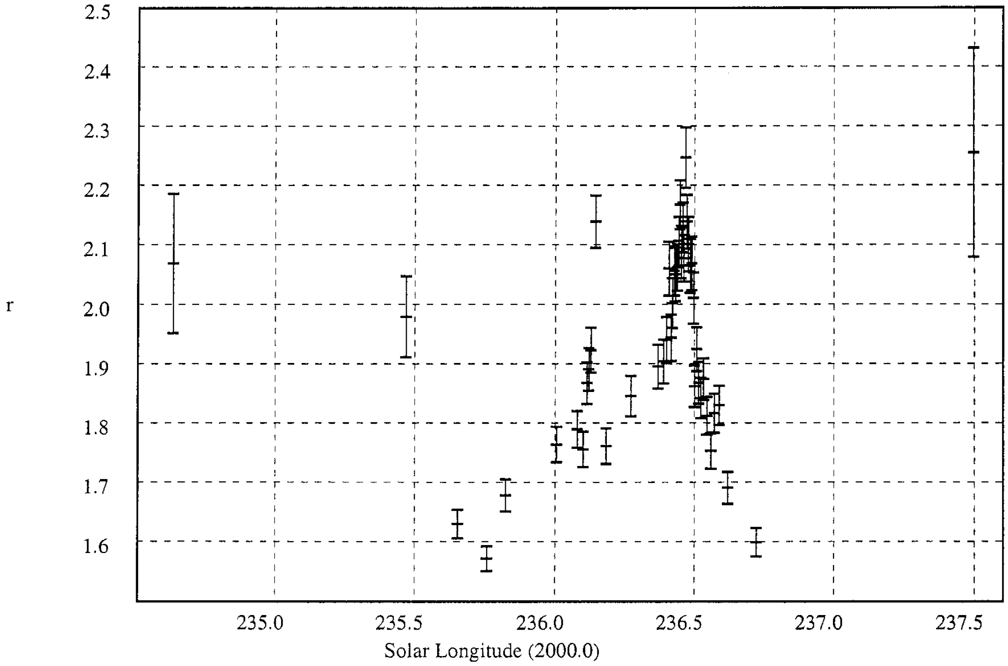

Figure 1 – Profile of the population index of the 2001 Leonids.

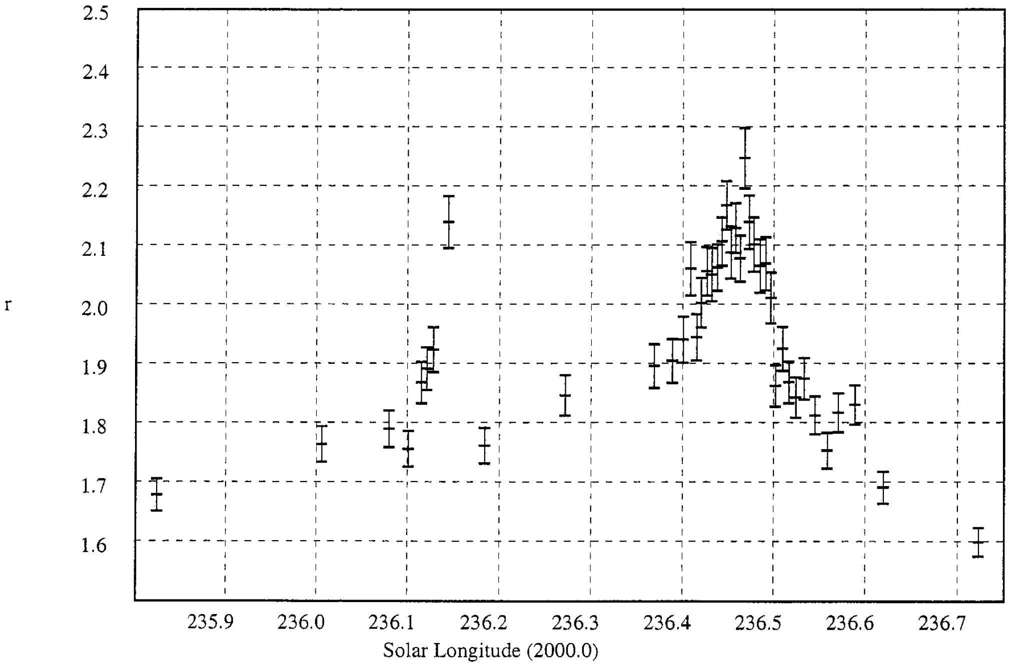

Figure 2 – Magnification of the population index profile near the two main maxima.

The two clear peaks coincide—at first glance—with the activity maxima of the Leonids. It is commonly assumed that we observe an abundance of faint meteors once the Earth is passing through the actual young dust trail. The periods before, in between, and after the peaks show population indices below 1.9, which is lower than typically observed in other major showers ($r \approx 2.0$). An abundance of bright meteors and several fireballs were indeed noted by the observers.

2001JIMO...29..187A

The highest population index of the first r-peak is found for $\lambda_\odot = 236.^{\circ}14^{+0.03}_{-0.01}$ with $r = 2.14 \pm 0.05$; the second r-maximum peaks at $\lambda_\odot = 236.^{\circ}465 \pm 0.^{\circ}005$ with $r = 2.25 \pm 0.05$. The additional spike at $\lambda_\odot = 236.^{\circ}445 \pm 0.^{\circ}005$ could be related to the transit through the 9-revolution trail.

3. Activity profile analysis

Despite the large number of observations for both storms over America and Asia, the construction of the activity profile was not straightforward. The same averaging as in [4] was used. The analysis routine adapts the bin size according to the data available. In contrast to past attempts, we used the number of observing intervals, instead of the number of meteors, to determine the bin size. The latter would emphasize the results of high-perception observers unless perception correction is applied thoroughly for all the observers participating.

Now, an optimum number of 20 observing periods was given for the averaging. The bin size was not allowed to fall below $0.^{\circ}0022$ (slightly above 3 min) as well as to exceed $0.^{\circ}1$ (2.4 hours). The upper limit helps bridging periods with poor observational coverage. The lower limit is necessary to ensure a fairly constant binning in periods for which very large numbers of intervals are available. If there would be no limit, the routine will reduce the bin size quickly to one minute, but, at the same time, drop almost all of the observing periods, since the length of these periods must not exceed the length of the bin. The behavior of the algorithm without lower bin-size limit would be highly irregular. The application of the lower limit will result in 50–80 observing periods per average (a factor of 3–4 higher than the preset value), as presented in Table 1. Setting the lower limit will include periods of at mos 3 minutes duration, regardless of how much the optimum number of periods (20) is exceeded. No periods longer than 3 minutes are used in the high-resolution part of the activity graph.

Table 1 – Overview of predictions and observed activity of the 2001 Leonids. The two models refer to [2] and [1], respectively. The peak times with exclamation marks are the main maxima, whereas the other times denote slight enhancements of activity with medium significance. Model times in brackets are tentative associations with observed features. The number of individual observing periods is given as "Per."

Dust trail	Models		Observations			
	McNaught Asher	Lyytinen, Nissinen, van Flandern	$\lambda_\odot$ (J2000.0)	November 18 UT	ZHR	Per.
7-rev	($09^{h}10^{m}$)	–	$236.^{\circ}082$	$09^{h}21^{m}$ (!)	680 ± 60	19
7-rev	$09^{h}55^{m}$	$10^{h}28^{m}$	$236.^{\circ}137$	$10^{h}39^{m}$ (!)	1620 ± 40	75
7-rev	($11^{h}00^{m}$)	–	$236.^{\circ}154$	$11^{h}03^{m}$ (!)	1610 ± 60	37
6-rev	–	($12^{h}00^{m}$)	$236.^{\circ}179$	$11^{h}39^{m}$	650 ± 40	19
6-rev	–	($12^{h}00^{m}$)	$236.^{\circ}195$	$12^{h}01^{m}$	520 ± 40	19
–	–	–	$236.^{\circ}262$	$13^{h}40^{m}$	400 ± 40	19
9-rev	$17^{h}24^{m}$	$18^{h}03^{m}$	$236.^{\circ}448$	$18^{h}02^{m}$	2830 ± 70	66
4-rev	$18^{h}13^{m}$	$18^{h}20^{m}$	$236.^{\circ}458$	$18^{h}16^{m}$ (!)	3430 ± 90	39
	–	–	$236.^{\circ}467$	$18^{h}30^{m}$ (!)	3010 ± 70	55
11-rev	$18^{h}43^{m}$	$19^{h}10^{m}$	$236.^{\circ}491$	$19^{h}04^{m}$	1840 ± 60	47

General restrictions excluded observing periods where the total correction $r^{(6.5-\mathrm{lm})} F c_\mathrm{p} / \sin h_\mathrm{R}$ is larger than 5. Here, the limiting magnitude is denoted by "lm," the field obstruction correction is F, individual perception coefficients are c_p, and h_R is the radiant elevation. Additionally, the latter was limited to $h_\mathrm{R} > 20^\circ$ to avoid the influence of non-geometrical effects in the radiant altitude correction.

The time correction for the topocentric encounter of the Earth with the Leonid meteoroid stream was applied according to [5]. Since the influx angle of the stream with the ecliptic is small and positive, southern geographic latitudes approach any stream structure significantly earlier than northern latitudes. The results presented in Table 1 refer to the encounter of the Leonids' orbital plane with the center of the Earth. Observers in Australia should thus detect the dust trail 10 minutes earlier than the topocentric encounter; observers in Mongolia had largest delays of 4 minutes shortly after radiant rise.

A very puzzling picture emerged for the first storm over American geographical longitudes. While all observers agreed upon a peak near $10^{h}40^{m}$ UT, a secondary maximum was detected near 11^{h} UT, most strikingly by a group of three observers. These amateurs enjoy good meteor perception, but the problem was not the level of their ZHRs, but the presence of a clear structure not obvious from the remaining data set. Only a very detailed—actually oversampled—profile of the American Leonid peak, which does not include the aforementioned observers, revealed a second spike of activity near 11^{h} UT with the same ZHR level as the clear maximum of $10^{h}40^{m}$ UT. The structure was just averaged out due too less data available for the northwestern American morning hours. Figure 3 shows the profile omitting the three observers mentioned; note that the bins for the averages are too small, and variations are not necessarily significant.

A look into first results from image-intensified video systems gives more trustworthiness to the second American peak. The video system of the *Arbeitskreis Meteore* operated in New Mexico shows two peaks: one at $10^{h}39^{m} \pm 5^{m}$ UT and the other at $10^{h}57^{m} \pm 5^{m}$ UT. The video camera of Osamu Okamura, who flew from the USA to Japan to record both storms, shows peaks at $10^{h}45^{m} \pm 5^{m}$ UT and $11^{h}08^{m} \pm 5^{m}$ UT, respectively. The route reached geographical latitudes with topocentric correction of about 3 minutes. Since he moved north of the Leonid influx direction, he saw the shower peak later than observers at lower latitudes. This fact makes his times match well with the *AKM*, system which only needs a very small topocentric offset. We cannot give an evaluation of the statistical significance of these data here, and look forward to the activity analysis of the operators of these video systems.

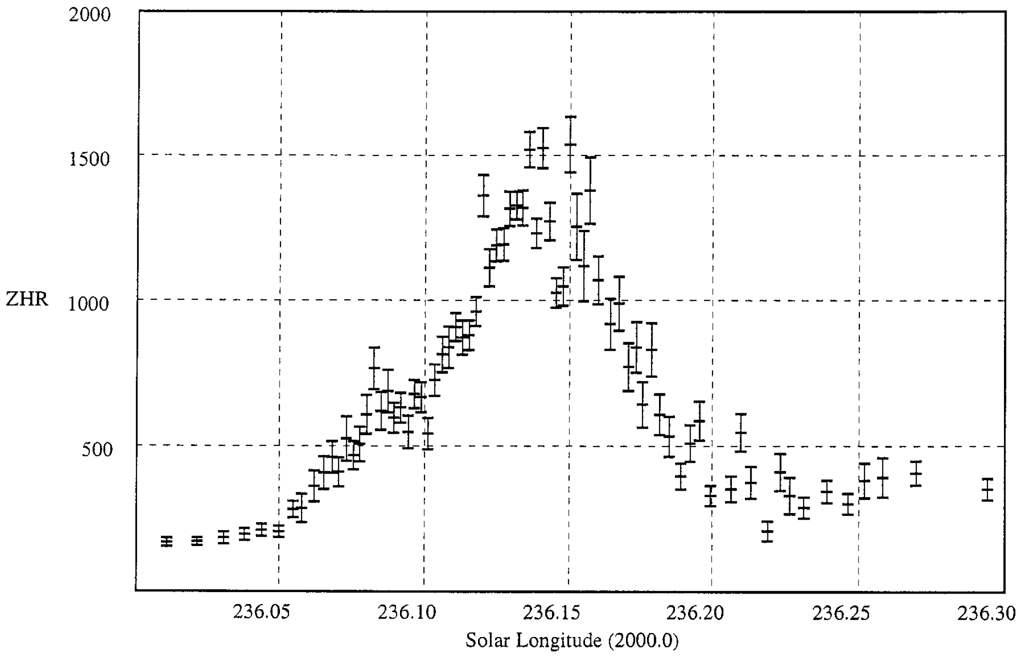

Figure 3 – Oversampled ZHR graph of the first peak as seen from American geographical longitudes. The diagram is intended to reveal a hidden second peak near 11^{h} UT. Variations may suffer from merely statistical fluctuations.

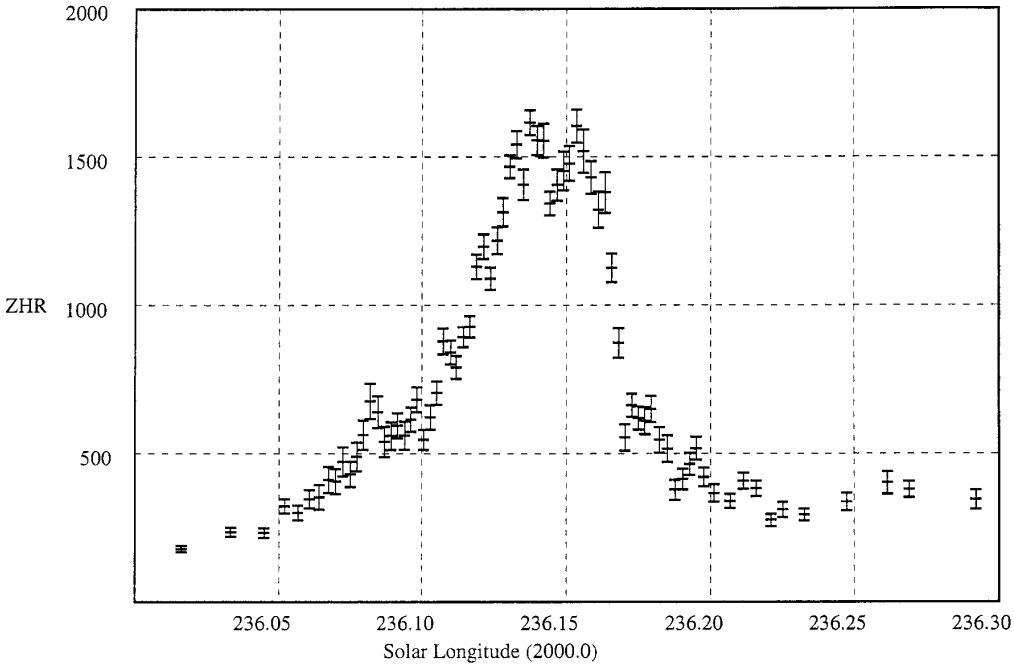

Figure 4 – Final profile of the first 2001 Leonid maximum as seen from American geographical longitudes.

Forward-scatter and radar data are also available, but the temporal resolution usually published is very coarse. The Ondřejov radar shows two peaks at $10^{\rm h}45^{\rm m} \pm 5^{\rm m}$ and $11^{\rm h}05^{\rm m} \pm 5^{\rm m}$, but the actual maximum occurred at $10^{\rm h}05^{\rm m} \pm 5^{\rm m}$ [6]! The topocentric encounter was about 2 minutes ealier, that is, the two spikes in the Ondřejov radar data match the observed peaks very well. Entirely early is the maximum as recorded by the SKiYMET radar at Resolute Bay, Canada. Given the fact that correction for topocentric stream encounter is as high as 10 minutes, we arrive at a main peak time of $10^{\rm h}20^{\rm m} \pm 5^{\rm m}$. The other SKiYMET radars did not record the storm [7].

Finally, a number of perception coefficients were deduced from three periods before and in the first American peak, from the range $\lambda_\odot = 235^\circ\!.128$–$236^\circ\!.139$. We have applied the resulting factors which were as high as 2.2–2.6 for the three "double-peakers." A recalculated profile of the entire maximum is shown in Figure 4. We obtain the following quantities from the graph: $\lambda_\odot = 236^\circ\!.137 \pm 0^\circ\!.003$ (November 18, $10^{\rm h}39^{\rm m} \pm 4^{\rm m}$ UT) with ZHR $= 1620 \pm 40$ and $\lambda_\odot = 236^\circ\!.154 \pm 0^\circ\!.003$ ($11^{\rm h}03^{\rm m} \pm 4^{\rm m}$ UT) with ZHR $= 1610 \pm 60$.

The fine structure of the American peak may also be visible in the profile of the population index. A recalculated graph with higher resolution did not reveal, however, a significant double peak. The scatter in the data becomes too large due to highly reduced meteor numbers in each average.

The Asian Leonid storm is shown in Figure 5. The highest activity level was observed at $\lambda_\odot = 236^\circ\!.458 \pm 0^\circ\!.002$ (November 18, $18^{\rm h}16^{\rm m} \pm 3^{\rm m}$ UT) with ZHR $= 3730 \pm 90$. Additional enhancements are found to either side of the highest peak, namely at $\lambda_\odot = 236^\circ\!.448 \pm 0^\circ\!.002$ ($18^{\rm h}02^{\rm m} \pm 3^{\rm m}$ UT) and $\lambda_\odot = 236^\circ\!.467 \pm 0^\circ\!.002$ ($18^{\rm h}30^{\rm m} \pm 3^{\rm m}$ UT).

It is always good to check the profile on changes when the selection of observers is changed. A second graph of the Asian storm is shown in Figure 6 involving only observing periods with $\text{lm} \geq +5.8$. The times of the three spikes are almost identical, but the level of activity is lower. The average limiting magnitudes for this profile is between +6.2 and +6.4. As the amount of data is still very large, we suggest to consider the results from this profile final.

2001JIMO...29..187A

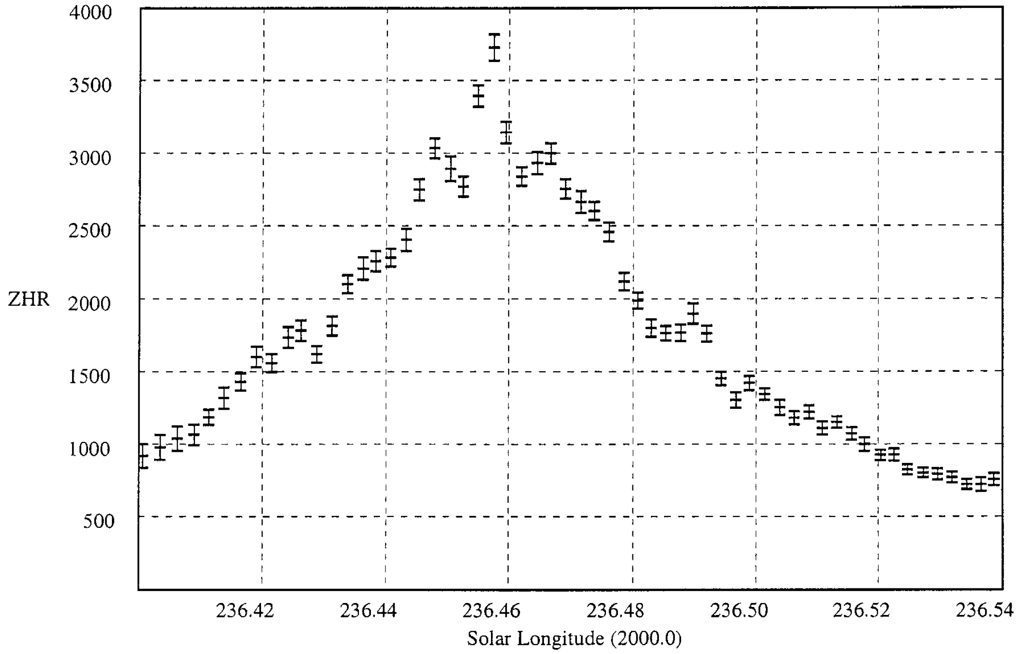

Figure 5 – Magnification of the second set of 2001 Leonid peaks as observed from Asian geographical longitudes.

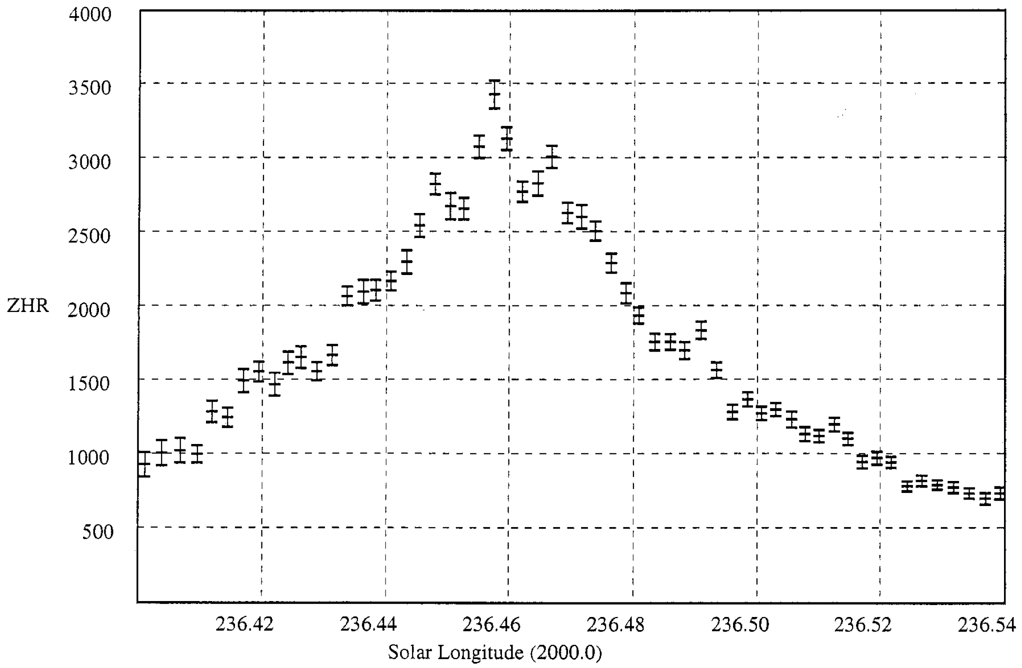

Figure 6 – Final profile of the Asian 2001 Leonid maximum. Observations with lm ≥ +5.8 were used in the averaging procedure.

Accounting for possible binning effects, we will give error margins for the final peak times which are larger than the actual bin size. These times are $\lambda_\odot = 236\overset{\circ}{.}458 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}16^{\rm m}\pm 4^{\rm m}$) with secondary enhancements at $\lambda_\odot = 236\overset{\circ}{.}448 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}02^{\rm m}\pm 4^{\rm m}$) and $\lambda_\odot = 236\overset{\circ}{.}467 \pm 0\overset{\circ}{.}003$ (November 18, $18^{\rm h}30^{\rm m} \pm 4^{\rm m}$).

4. Discussion

A first detailed profile of the Leonid meteor storms of 2001 was calculated. The main peaks at $10^{h}39^{m}$ UT and $18^{h}12^{m}$ UT match the predicted times of the 7-rev. and 4-rev. dust trails well. While the American maximum occured 11 minutes after the prediction of Lyytinen et al., and 44 minutes after the prediction of McNaught and Asher, the Asian peak was quite in time to fall between the $18^{h}13^{m}$ UT prediction by the latter and the $18^{h}20^{m}$ UT prediction of the model of Lyytinen et al.

The youngest trails up to 4-rev. in age are apparently the easiest to predict with accuracies of a few minutes. The $18^{h}02^{m}$ UT peak of the visual graph can be associated with the 9-rev. trail according to the prediction of Lyytinen et al. The result of McNaught and Asher is more than half an hour early, but so is nodal encounter with the trail also in the model of Lyytinen and colleagues! Only the consideration of non-gravitational effects brings the 9-rev. trail to times near 18^{h} UT. The same holds obviously for the 7-rev. trail for which the purely gravitational models result in $10^{h}05^{m}$ and $09^{h}55^{m}$ UT, in [1] and [2], respectively. See also Table 1.

We conclude that there was a second activity peak seen from American locations after that of the 7-rev. trail. Fatigue and reduced attention after the "fulfilled" prediction of the $10^{h}40^{m}$ peak may have resulted in understated Leonid numbers for some observers. The second peak is, however, too early for an association with the 6-rev. trail which was expected after 12^{h} UT.

We would also like to mention the possibility of a hollow stream structure. Such a hollow stream may be observable as a double-peak in the activity. The American maximum would then actually be centered at $10^{h}52^{m}$ UT with the two peaks being the two dense regions of the same tube-like structure. The analysis of the 1998 Leonid peak near $\lambda_{\odot} = 235.^{\circ}3$ (faint-meteor peak) showed a clearly bimodal population index profile, whereas a double peak in the ZHR profile was much harder to distinguish [8]. The bimodal structure may be associated with the encounters with the relevant 1-rev. and 2-rev. trails in 1998, though [9].

Despite the large number of observations, we found distinct influence of the individual perception of observers on the average activity profiles. This contrasts with earlier findings in global analyses of meteor showers. It is likely that the exceptional situation of a meteor storm results in much stronger scatter of individual data points. The actual ZHR level of both maxima may thus alter in a future full analysis of the 2001 Leonids in which perception coefficients for many observers will be derived.

5. Instructions for observers emerging from the analysis

Data input was (and is) a tremendous job, even for eight people. A layperson might wonder why this needs so much time, but each observation looks very different from another, and observations are often not consistent, so that input officers have to ask the observers which of two conflicting pieces of information is correct. In the rest of this section, we would like to stress some points that could further improve the quality of the data and make data input easier:

- *IMO codes for observers and observing site* are fixed by the input officers. Name codes do not always follow the rule "first three letters of the second name plus first two letters of the first name," so do not write codes that have not been fixed yet. New site codes are only fixed if your observing place is not within a radius of about 30 km from an old observing site: this is sufficiently accurate for visual purposes.
- *Limiting magnitudes are crucial.* Each observer should measure his or her own limiting magnitude for each observation (observers under the same sky may differ by up to one magnitude!). At good weather conditions, limiting magnitudes do not change very fast (unless the Moon is rising or twilight begins). The *IMO* standard method for measuring limiting magnitudes is very easy: count stars in three or more standard fields (see `http://www.imo.net/visual`) around your center of field of view and average the corresponding limiting magnitudes given by the tables.

- *Clouds are a severe problem*, if they are moving fast or take more than 20% of your visual field (which is approximately a circle of 50° radius around your center of field of view).
- Make sure that you are *looking at a point higher than* 30° above the horizon, because, otherwise, your field of view is obstructed by the Earth. If the population index is low, this may be balanced by more visible meteors, bute note that the observing situation results in uncertain corrections upon deriving meteoroid stream parameters.
- For a meteor storm, *choose observing periods of about 1 or 2 minutes*. Magnitude distributions can contain two or three such 1-minute periods, but always remember that there may be a loss of information due to a coarse breakdown. Make sure that start and end of an interval for a magnitude distribution always coincide with start respectively end of a smaller interval you give for the rates. A breakdown of magnitude distributions is *also required for other meteor showers*.
- Give effective observing times, T_{eff}, shortened by the time you did not watch the sky (noting down data for example). Caution: $1^{\text{h}}37^{\text{m}}$ to $1^{\text{h}}39^{\text{m}}$ is a 2-minute, period not 3 minutes.
- The *Visual Meteor Database* (*VMDB*) only contains data about rates and magnitudes; information about trains or colors is not stored in it. For meteor storms, you have to report little information on many meteors instead of much information on few meteors. For the rest of the year, however, you can store your data about trains, colors and paths in the *VISDAT* archive. A global *VISDAT* computer archive is planned and would allow even the search for new showers. Input of observations is then distributed to the individual observers, and the *VMDB* can be updated automatically.

Availability of data

The full data set of visual Leonid observations are available from Rainer Arlt. Further analysis of the data is most welcome. For enquiries, please refer to the e-mail address below.

Acknowledgments

The authors are most grateful to the visual observers who contributed with their data to this analysis. The enormous work of data input and utilization was not only done by the authors, but also by Jürgen Rendtel, Felix Bettonvil, Darja Golikowa, and Orlando Benitez to whom we do express our gratitude. We would also like to thank Sirko Molau and Marc Gyssens for their valuable comments, the former also for providing the video data.

References

[1] E. Lyytinen, M. Nissinen, T. van Flandern, "Improved 2001 Leonid Storm Predictions from a Refined Model", *WGN* 29, 2001, pp. 4–12.

[2] R.N. McNaught, D. Asher, "The 2001 Leonids and Dust Trail Radiants", *WGN* 29, 2001, pp. 156–164.

[3] P. Brown, B. Cooke, "Model predictions for the 2001 Leonids and implications for Earth-orbiting satellites", *Mon. Not. R. Astron. Soc.* 326, 2001, pp. L19–L22.

[4] R. Arlt, M. Gyssens, "Bulletin 16 of the International Leonid Watch: Results of the 2000 Leonid Meteor Shower", *WGN* 28, 2000, pp. 191–204.

[5] R.N. McNaught, D.J. Asher, "Variation of Leonid Maximum Times with Location of Observer", *Meteorit. Planet. Sci.* 34, 1999, pp. 975–978.

[6] P. Pecina, P. Přidal, R. Štork, "Leonids 2001 from the Ondrejov Backscatter Radar", `http://www.asu.cas.cz/štork/leo_2001`, November 19, 2001.

[7] Mardoc Inc., "SKiYMET Observations of the November 2001 Leonids Meteor Storms", `http://members.rogers.com/leonidsbyradar/2001.htm`, November 2001.

[8] R. Arlt, P. Brown, "Bulletin 14 of the International Leonid Watch: Visual Results and Modeling of the 1998 Leonids", *WGN* 27, 1999, pp. 267–285.

[9] R.N. McNaught, D. Asher, "Leonid Dust Trails and Meteor Storms", *WGN* 27, 1999, pp. 85–102.

Authors' addresses

Rainer Arlt, Friedenstraße 5, D-14109 Berlin, Germany, `visual@imo.net`.
Javor Kac, Na Ajdov hrib 24, SI-2310 Slovenska Bistrica, Slovenia, `javor.kac@orion-drustvo.si`.
Vladimir Krumov, jk. Vladislavovo, bl. 401, 9-149, BG-9000 Varna, Bulgaria, `X3M@club26.com`.
Jan Verbert, Drabstraat 284, B-2640 Mortsel, Belgium, `jver@urania.be`.
Andreas Buchmann, Chaletstraße 7, CH-8600 Dübendorf, Switzerland, `andreas.buchmann@access.unizh.ch`.