On fragmentation of meteoroids in interplanetary space

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Abstract. A possible fragmentation of meteoroids in interplanetary space inferred from grouping of particles in meteor streams is discussed. There is a conviction maintained by many observers that meteors within the streams are observed to be clustered in pairs or larger groups more frequently than one could expect from random distribution. The rate of dispersive effects indicates that the lifetime of any such a group of meteoroids is very limited. Therefore, if real, the pairs or groups must be due to recent fragmentation of larger meteoroids.

Analyses based on visual observations of meteor streams lead to contradictory results. More conclusive are analyses based on radio measurements, which present a negative result concerning the permanent meteor showers with the stream structures at their middle and late evolutionary stages, and an indication of a positive result for younger dense stream structures of recent origin. Analysis of the 1969 Leonid display obtained by the Springhill high-power radar shows that about 10 % of the population around the shower maximum is associated in close groups, within a distance up to of about 10 km and confined to an effective stream width comparable to the diameter of the Earth. The recent Leonid returns with the storm in 1999 provided a possibility to verify a non-random grouping of particles within this young filament of the stream. The analysis and results based on TV observations of the storm are presented and discussed.

Key words: meteoroids – meteor showers – Leonids

1. Introduction

It has been repeatedly suggested on the basis of visual and radar observations that meteors often appear in pairs or larger groups within short time intervals. They usually have some similar characteristics (brightness, path etc.), so they easily attract the observer's attention. This phenomenon could be a result of

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chance and only an analysis of its frequency can give an answer whether the grouping is real or not. It is apparent that the pairs of unequal size, due to the solar radiation pressure and other non-gravitational effects, must rather quickly disintegrate.

If the pairs and groups are really observed, this would testify that meteors have tendency to crumble and this fragmentation is frequent near the Earth. The possible reality of this grouping has already been studied by a number of authors.

Most analysis of visual observations from this point of view refer to major meteor showers, which only have frequencies sufficient for such statistics. Millman (1936) examined the Perseids and Leonids. The question of grouping for sporadic meteors was studied by Hoffleit (1937). Millman found negative results for the Leonids, but slightly in favour of a non-random grouping for the Perseids. Simultaneous observations of the Perseids on a long baseline in 1950 and 1951 indicated that the stream was composed of separate meteor clouds of different size (Savruhin, 1951).

More reliable are the results obtained by radio measurements, primarily because radio data are more extensive than visual data and the time of meteor apparition can be determined with a higher accuracy. A common result of all these analyses, except for those by Wylie and Castillo in 1956 (see Bowden and Davies, 1957) and by McCrosky (1957), was the absence of grouping of meteors over a random level (Shain and Kerr, 1955; Briggs, 1956; Bowden and Davies, 1957; Poole, 1965).

According to Bowden and Davies (1957) the equipment of Wylie and Castillo, who found a significant excess of 30 seconds sampling intervals with five or more echoes over the number expected from the Poisson distribution, was not capable to distinguish satisfactorily fluctuating echoes and close groups, which has led to an excess of spurious groups.

The second positive evidence presented by McCrosky (1957) analysing the maxima of the Perseids and Geminids suggested that there was a significant excess of the observed pairs or triplets of meteor echoes in one second intervals compared with that predicted by the Poisson distribution. However, if McCrosky's data are treated for each night separately, in 30 minute intervals the distributions are in agreement with the random distribution.

Similar negative result was obtained in an analysis of two types of radio data, with more than 32 000 meteor echoes (7 400 from low power radar in Ondřejov and 25 200 from high power radar in Dushanbe) by Porubčan (1968), covering the activity of the major meteor showers and the sporadic background. This result has been found even in the range of very faint meteors corresponding to the limiting magnitude of about +13.5 (Dushanbe).

All these analyses referred to the observations of permanent showers, i.e. to the stream structure at their middle and later evolutionary stages and for all these streams of considerable dispersion (high age), the result seems to be definitely negative. Therefore, it appeared desirable to apply a similar analysis on a shower of recent origin as the Leonids 1966, 1969 and 1999, where the conditions of the dispersive process at the earliest evolutionary phase may be different.

2. Methods of analysis

Three methods of analysis have been applied to our search for possible non-random grouping of meteors:

2.1. Time distribution

A random frequency distribution of the time intervals between successive echoes is described by the exponential law

$$n_t = n\frac{dt}{T}exp(-\frac{t}{T}) \tag{1}$$

where, n_t is the expected number of intervals between t and $t+dt$, n is the total number of intervals, and T is the mean interval. Integration of (1) yields the number of echoes in any time interval.

2.2. Poisson distribution

Similarly, if the occurrance of meteors is random, the distribution of rates within a sampling interval will be given by the Poisson relation

$$n_i = n\frac{a^i}{i!}exp(-a) \tag{2}$$

where n_i and n are respectively the expected number of sampling intervals containing i = 0,1,2,... meteors, and the total number of intervals; a is the mean number of meteors in a unit sampling interval.

2.3. Range distribution

The fourth method (Porubčan, 1968) is based on the distribution of distances of echoes and can be applied only to radar observations providing range-time records from which the ranges of individual echoes can be obtained.

The spatial proximity of a pair of meteors means that they appear not only in a short time interval, but also in a narrow interval of distances from the observer. To verify the grouping, the differences of distances dR between successive echoes are to be compared separately for pairs of echoes which follow one after another in short time intervals (from 0 to t_1 sec), and separately for pairs which exceed the range of this interval (over t_2, $t_2 > t_1$).

If a grouping exists, one should expect that the relative number of dR for short time intervals (up to t_1 sec) exceeds that for larger time intervals (exceeding t_2).

3. Leonids 1969, 1999 and Lyrids 1982

The most intensive meteor storm ever observed so far were Leonids 1966 on Nov. 17, 12 UT (Kresák, 1993). According to visual observations the zenithal hourly rate at the peak reached 150 000 meteors. The storm was recorded also by meteor radars at Springhill, Canada. However, the record of the peak by the high power radar could not be reduced at all due to completely masked radar record by the overlapping echoes. The low-power radar record gave a peak rate of about 160 000 echoes per hour, however still approx. 30% of echoes in the record, were overlapped (McIntosh and Millman, 1970). Thus the records could not be used for an analysis of possible non-random grouping of meteors.

3.1. Leonids 1969

In 1969 another spectacular Leonid meteor storm was observed and recorded at the Springhill Meteor Observatory, Canada. The shower maximum obtained by the high-power radar (peak power near 3 megawatts) was not as high as in 1966 and quantitative data could be recorded. According to the low-power radar data (McIntosh, 1973) the 1969 shower had even higher proportion of short-duration echoes with a mass distribution exponent $s = 2.4$, while for the 1966 shower this exponent had a value of $s = 2.2$. The peak appeared on Nov. 17 at 09 UT and the data analysed consist of 14 160 records obtained around the shower maximum (08:30 – 09:55 UT). The echo counts (all echoes, uncorrected for sporadic background) in one minute intervals are plotted in Fig. 1 (with two 1-minute breaks at 09:15 and 09:31 UT). The peak appeared between 09:02 – 09:03 UT and the whole maximum is very narrow one, only a few minutes in duration, which corresponds to the thickness of the densest part of the filament to a few thousand kilometers.

Three methods of analysis for a search for non-random grouping were used: time, Poisson and range distribution (Porubčan, 1974).

Formula (1) is valid if the time intervals between successive echoes are known precisely. The timing accuracy with which the appearance of echoes can be read from the records is of course finite, and if it is comparable to the average interval between successive echoes, the observed distribution must be corrected (Porubčan, 1968). The 1969 Leonid data were read off from the record with a timing accuracy of 0.1 second and no correction for this effect had to be applied.

The exponential law and Poisson distribution should be applied to the events which are approximately homogeneous in frequency. Rapid and systematic changes in frequency can generate spurious deviations from randomness. To avoid this possibility the data were divided into sets each of which was reasonable homogeneous but still large enough to give statistically valid results.

The data were divided firstly to successive 5-minutes interval sets and secondly into different sets with approximately equal one-minute frequencies. In this way different sets were obtained in which the observed distributions of the

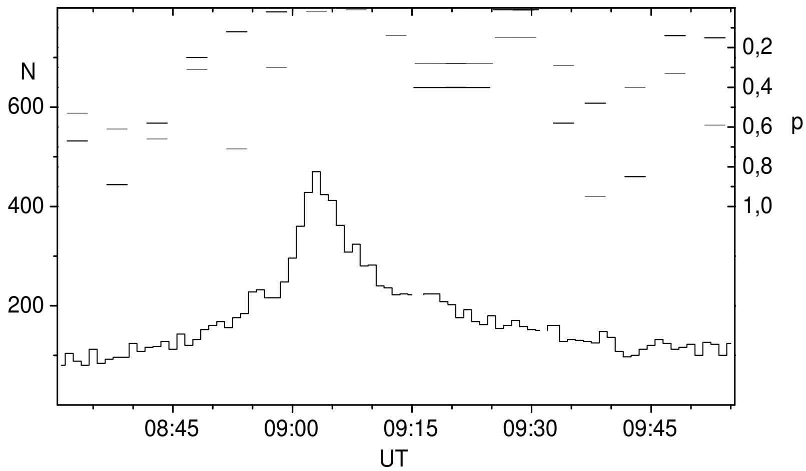

Figure 1. The echo counts in one-minute intervals of the Leonids on November 17, 1969 (08:30 – 09:55 UT, 14160 echoes) registered by the high-power radar in Springhill, Canada. Probabilities resulting from the chi-squared test (right ordinate) are represented by light lines (time distributions) and heavy lines (Poisson distributions).

time intervals were compared with those predicted by the exponential law (1). If any real grouping of echoes above a random level does exist, it should appear as an excess of observed counts over theoretical values in the wings of the fitted distributions, i.e. by increasing the relative number of the shortest and the longest intervals, and reduce the number of intervals around the average value. Differences between the observed and expected distributions were evaluated by the chi-squared test giving the probability with which the observed and expected sets resemble.

Fig. 2a,b shows two sets: (a) - a 5-minute interval before the shower maximum (08:30 – 08:35 UT, with 465 echoes) and a 1-minute interval at the peak activity (09:02 – 09:03 UT, with 461 echoes). The observed distributions are indicated by full lines and the theoretical ones by dashed lines. There are evident significant differences between both sets with the excesses of the observed intervals over the predicted ones for the shortest time intervals. This is not due to steeper frequency changes around the shower maximum which were compensated by the choice of the sampling interval.

As the antenna of the Springhill high-power radar was omnidirectional, the echoes may be sampled into spurious groups as the echoes appearing in the same time may be in fact at mutual distances of several tens of kilometers. To eliminate this possibility the data were reduced by a limitation according to the

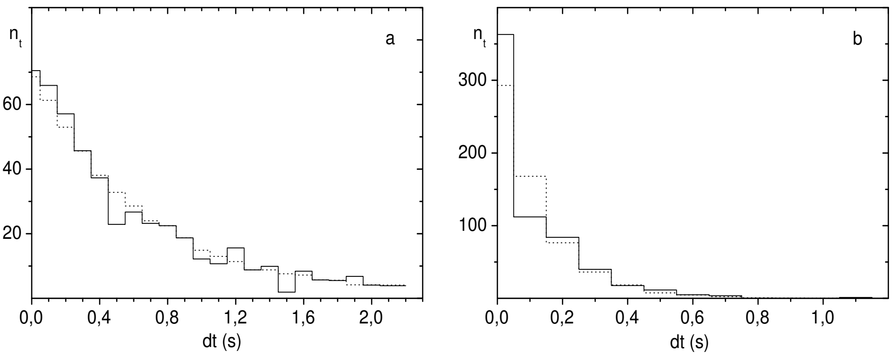

Figure 2. Leonids 1969: Comparison of the observed (full line) and expected (dashed line) time distribution. Fig. 2a shows a set from a 5-minute interval before the shower maximum (08:30 – 08:35 UT, 463 echoes) and Fig. 2b a set from a 1-minute interval at the peak of activity (09:02 – 09:03 UT, 461 echoes).

slant ranges of the echoes to 200 km.

Provided the meteor trails are observed by radar only at specular reflection, they are observed only in a small region of the atmosphere. As mentioned above the 1999 Leonids were represented chiefly by short duration echoes and thus fulfilled this condition completely. The Leonids with a high geocentric velocity of 71 $\mathrm{km\,s^{-1}}$ ionize higher in the atmosphere. As a reasonable upper limit of their height a value of 150 km was adopted, which for the zenith distance of the radiant at the time of maximum (38 degrees) corresponds to a slant range of about 200 km. This value was used as an upper rejection level. This limitation reduced the number of echoes in each set and removed possible marginal groups around this limit.

There is another effect which appears especially at high frequencies, namely the blending of echo images on the record, caused mainly by long-duration echoes. This effect reduces the number of shortest intervals and thus tends to mask any real grouping.

For a comparison with the Poisson distribution, the data were divided into the same sets as for the time distributions. The sets were then divided into 1.0 and 0.1 second sampling intervals in which the numbers of echoes were determined and compared with the theoretical numbers resulting from the Poisson distribution (formula (2)). Similarly, if a grouping of meteors exists, it would betray by elevating both wings of the observed distribution over theoretical one, and decreasing the centre.

Fig. 3a,b shows a comparison of the observed (full line) and expected (dashed line) Poisson distributions from a 5-minute interval set around the shower maximum (09:00 – 09:05 UT, 2054 echoes) for the 1-second (Fig. 3a) and for the

0.1-second (Fig. 3b) sampling intervals including i meteors. The true distribution with 0.1-second sampling intervals is distinctly dissimilar to the theoretical one.

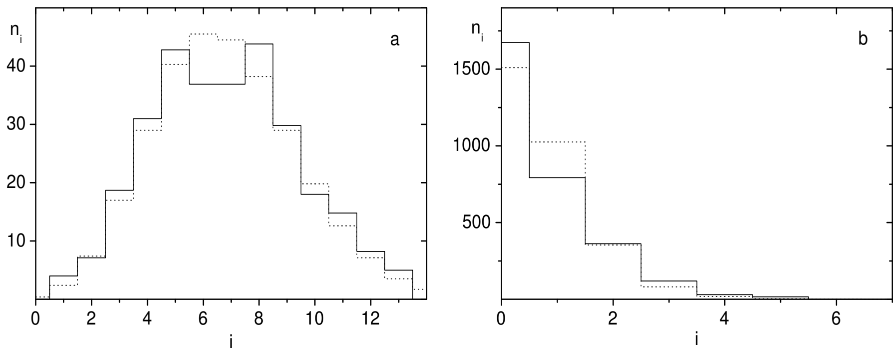

Figure 3. Leonids 1969: Comparison of the observed (full line) and expected (dashed line) Poisson distribution from a 5-minute interval set around the shower maximum (09:00 – 09:05 UT, 2054 echoes) for the 1-second (Fig. 3a) and 0.1-second (Fig. 3b) sampling intervals, including i meteors.

Similarly in Fig. 4 a,b there are the observed (full line) and the expected (dashed line) Poisson distributions of the 0.1-sampling intervals with i meteors for a 5-minute interval set from 08:30 – 08:35 UT (Fig. 4a, with 465 echoes), from a period preceding the maximum, and the 1-minute record at the shower maximum at 09:02 – 09:03 UT (Fig. 4b, with 461 echoes). Again, there is distinctly evident difference between the observed and expected distributions at the maximum in favour of real grouping of meteors. In the same way as for the time distributions, a limitation in slant ranges of each set was adopted in order to eliminate spurious groupings of echoes from the omnidirectional antenna.

The observations were also analysed by a method based on the distribution of the slant range differences between pairs of successive echoes, as a mutual proximity of a group of meteors means that they will appear not only within a short time interval but also within a narrow range of distances. The reality of grouping can be verified by deriving the differences of the distances dR between successive echoes which appear within a very short time interval and those which exceed this interval. The results of a such comparison are plotted in Fig. 5a,b, with the relative occurance of different values of dR for $dt = 0$ (full line) and for dt greater than 0.5 sec (dashed line).

Fig. 5a shows a 20-minute interval from the shower maximum (8:55 – 9:15 UT, containing 5884 echoes) and Fig. 5b is constructed for the data set 8:30 – 9:15 UT, with 9031 echoes. The differences between the histogram in both Figs. indicate a real grouping. The first interval for $dt = 0$ is less pronounced but is

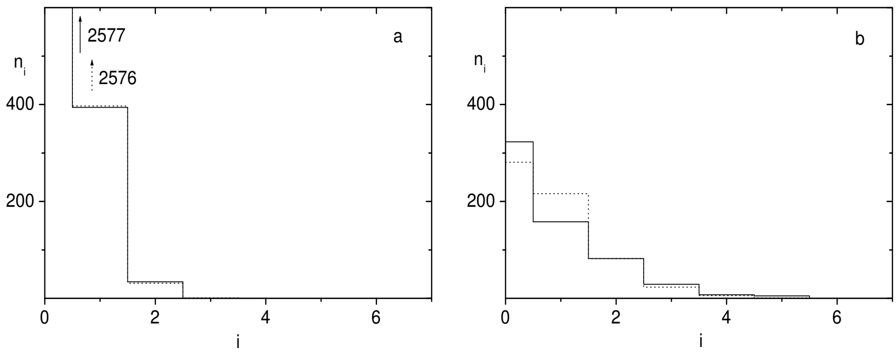

Figure 4. Leonids 1969: The observed (full line) and expected (dashed line) Poisson distribution for a set of 08:30 – 08:35 UT, 465 echoes (Fig. 4a) and a set of 09:02 – 09:03 UT, 461 echoes (Fig. 4b) for the 0.1-second sampling intervals including i meteors.

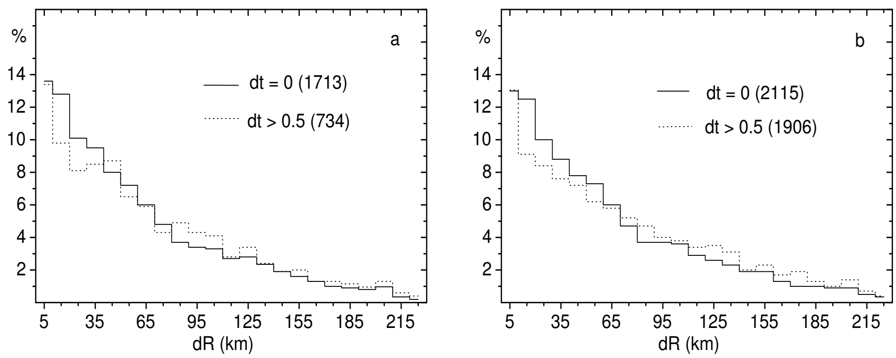

Figure 5. Leonids 1969: Relative occurance of different values of dR for $dt = 0$ (full line) and $dt \geq 0.5$ (dashed line). Fig. 5a shows a set from a 20-minute interval (08:55 – 09:15 UT, 5884 echoes) and Fig. 5b is constructed for the data set 08:30 – 09:15 UT, 9031 echoes.

mostly affected by the blending effect assessed for the maximum to of about 20%.

Application of the chi-squared test to 5-minute sets of echoes of $dR \leq 200$ km is shown in Fig. 1, where the probabilities p are plotted as light lines for the time distributions and heavy lines for the Poisson distribution.

According to the excess of the observed numbers of meteors in the Poisson distribution for the 0.1-second sampling intervals, the proportion of meteors within groups of two or more meteors, for the period around the maximum

(08:54 – 09:10), amounts to about 10 percent. However, this is a lower limit only because of the blending effect which was not taken into account. The dimensions of the groups are comparable with the size of the sampling interval, which is for the Leonids and 0.1 sec a distance less than 10 km, but according to the range distribution the upper limit for the dimensions of the groups may be as high as 40 km.

The clustering was observable over a period of about 25 minutes around the shower maximum and as the elongation of the heliocentric radiant of the Leonids from the Earth apex is 18 degrees, it can be found that the clustering is confined to an effective stream width of about 14 000 km. Thus the thickness of the layer where clustering occurs is comparable with the diameter of the Earth.

This finding may be indicative of a fragmentation process continuing after the release of meteoroids from their parent comet, in the central region of the stream which is mostly populated.

3.2. Lyrids 1982

The April Lyrids are known as a fairly low activity shower. In 1982, however, the shower surprised meteor observers with an activity which was many times the normal annual rate but lasted for only a short time. The enhanced rate was observed both visually and by radar.

Visual observations showed an exceptional outburst in Lyrid activity on April 22, between 06 – 08 UT, with a maximum at 06:50 UT (Adams, 1982). The storm lasted for 15 minutes between the half maximum points an 48 minutes between the quarter maximum points. The mean observed magnitude of +3.62 implied a predominance of smaller meteoroids.

The storm was observed also by the Springhill meteor patrol radar and since this Lyrid enhancement had appropriate characteristics of a young shower (very narrow width and a preponderance of small particles), the data were analysed for possible non-random grouping of meteors (Porubčan and McIntosh, 1987).

Two methods of analysis were used: comparison of meteor rates with a Poisson distribution and comparison of the time intervals between meteors with an exponential distribution. Of all the data only a limited area around the peak was searched for non-random clustering. This interval was divided into two sets: the first being a 25-minute period centered on the peak; and the second combining the 25-minute periods preceding and following the peak. However, no grouping of meteoroids over a random level in this Lyrid cloud was found.

Also another aspect concerning the exceptional activity of the 1982 Lyrids is of interest. Dense meteoroid clouds exhibiting activity bursts or meteor storms are usually situated close to the parent comet and their origin can be explained by a recent ejection process from the cometary nucleus. Quite different situation is observed in the 1982 activity enhancement of the Lyrids, when the corresponding dense filament was very distant from the parent comet Thatcher (1861 I). The burst occured about 120 years behind the comet with its orbital period of 415 years. An alternative explanation of the existence of such a dense filament of meteoroids so far from the parent comet may be its origin in a secondary larger chunk or a boulder loosed from the comet earlier. The chunk could disintegrate later on, producing a filament of non-ejected meteoroids moving in similar orbits for a relatively longer time (Porubčan et al. 1992). An estimate of the cross-section of the filament based on the observed rates provides a width of about 90 000 km and considering low ejection velocities observed at splittings of comets (up to few m/s), such a secondary larger body could be released from the comet of about 30 000 years ago.

3.3. Leonids 1999

Another unique opportunity to verify a non-random distribution of meteoroids within a young stream was the Leonid storm observed in 1999 on November 18 at 02:02 UT, when the Earth crossed a filament of meteoroids released from the parent comet (55P/Tempel-Tuttle) three revolutions ago (in 1899).

The peak with the ZHR = 3 700 (visual observations, Arlt et al. 1999) appeared exactly according to the prediction (McNaught, Asher, 1999). The storm was observed also by a set of TV cameras on board airplane ARIA (Leonid MAC 1999). As we have at disposal a 52-minute record from the peak of the storm (01:51 – 02:43) from the Institute of Space and Astronautical Science, Japan for a treatment, a partial analysis of this exceptional event could be made.

The record is from the observations by a High-Definition TV Digital Video Camera with Image Intensifier (HD-TV-II) having a field of view 60°x35° and the limiting stellar magnitude +7. The observations were carried out during the flight at a height of 11 km with the camera directed due to north near the horizon.

Two methods for the analysis of a non-random grouping of meteoroids in this filament were applied: the observed distributions were compared with the exponential time and Poisson distribution (for 5, 1 and 0.1-second sampling intervals) and the deviations were evaluated by the chi-squared test.

The observations analysed so far are from a 10-minute record, 01:51 – 02:01 UT, containing 1633 meteors (Fig. 6). The observed and expected distributions are plotted in Fig. 7 (time intervals) and Fig. 8 (Poisson distribution).

A similar analysis aiming at possible clustering of meteoroids over a random level wihin the young 1999 Leonid stream was made by Gural and Jenniskens (2000). Their analysis was also based on the observations on board the same airplane ARIA, but with an intesified CCD camera pointed in the opposite direction towards the low southern horizon. By comparing the expected time distribution with the observed one at the shower peak (01:54 – 02:06 UT, Nov. 18, 1999) no enhancement or clumping of meteoroids down to time scale of the video frame rate of 66 milliseconds was found.

In our analysis the times of appearance of meteors on the video record were read off with the temporal resolution of 33 milliseconds. The probability resul-

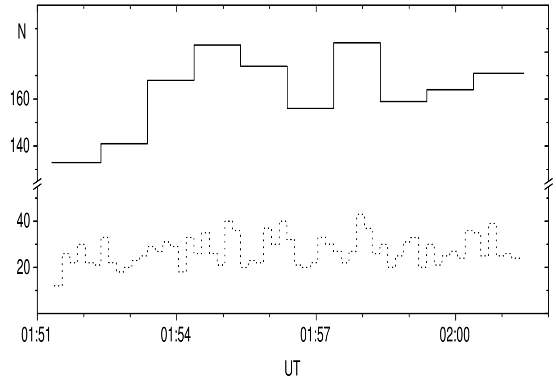

Figure 6. The counts of the analysed Leonids 1999 in one minute intervals (full line) and 10-second intervals (dashed line).

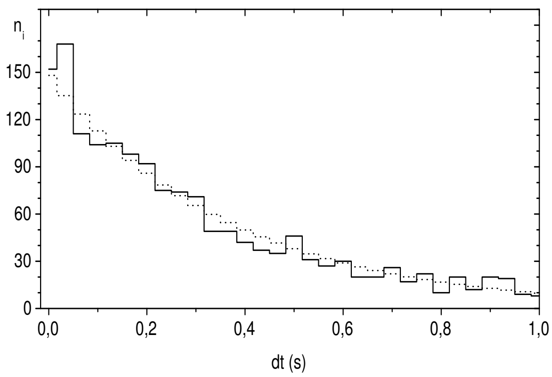

Figure 7. Comparison of the observed (histogram) and expected (curve) time distribution of the Leonids 1999 (01:51 – 02:01 UT, Nov. 18).

ting from the chi-squared test for the time distributions (Fig. 7) is 0.024 and for the Poisson distribution (Fig. 8) with 0.033-second sampling intervals is 0.093. Results obtained exhibit that both the time and Poisson distribution show the deviations in favour of possible grouping of meteoroids over a random level, as for the time intervals so for 0.033-second sampling intervals at the peak of the storm. As evident from Fig. 6, there is observed no systematic change in frequency which could influence the exponential law and Poisson distribution in favour of spurious deviations from randomness. Thus the results obtained can be considered for positive and in favour of a progressive fragmentation of meteoroids in the interplanetary space.

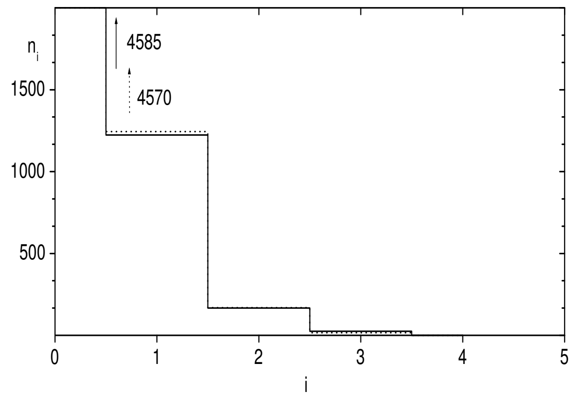

Figure 8. The observed (dashed histogram) and expected (open histogram) Poisson distributions for a 10-minute set (01:51 – 02:01 UT, Nov. 18, 1633 meteors) of the Leonids 1999 for the 0.033-second sampling intervals.

4. Conclusions

The analysis of the Springhill meteor radar data from the great Leonid shower in 1969 suggests a non-random clustering within the core of this young stream filament.

The effect was present for about 25 minutes about the shower maximum (09:02 UT, Nov. 17, 1969), but absent before it. The region of positive results has a cross-section of about one diameter of the Earth and at least 10% of the population appear to be concentrated in close pairs or dense clusters in the core of the filament. The dimensions of the groups may be up to about 40 km. The observations are indicative of a fragmentation process in the central part of the young meteoroid stream filament continuing after the meteoroids are released from the nucleus of the parent comet.

No grouping of meteoroids over a random level was found in the 1982 Lyrid meteor storm observed in the orbit about 120 years behind the parent comet Thatcher (1861I).

The 1999 Leonid meteor storm presents additional evidence for a possible clustering of meteoroids over a random level within a young filament of the Leonid meteoroid stream.

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