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Prediction of meteoroid stream structure based on meteoroid fragmentation

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Abstract. Every day, large number of meteoroids enter the Earth's atmosphere and deposit their mass either in atomic form or in ionic form depending on whether it has undergone ablation or fragmentation. The heavier meteoroids undergo fragmentation while the lighter ones are more prone to ablate. In this paper, we would like to speculate meteoroid stream structure of Leonid meteor shower based on fragmenting meteoroids. A 23 revolutions old meteoroid trail left behind by the comet 55P/Tempel-Tuttle in the year 1213 AD, which instigated Leonid meteor shower in the year 2010 is considered for our study. We have calculated mass of the meteoroids, echo durations and percentage of fragmentation. From the observed echo durations of meteoroids, estimated masses and from the percentage of fragmentation, we visualize the stream structure to be like the lighter particles wrapping up the heavier ones. The results we draw from these three different studies are matching with each other. To our knowledge, we are the first to speculate on the meteor stream structure based on fragmentation and making it a new tool in meteor stream evolution. Based on echo durations, it has been observed that 72% of the activity during the shower is contributed by lighter particles of the stream. It is found that about 20% of the meteoroids have undergone fragmentation indicating the minimal role of heavier particles ($>10^{-6}$ g) during Leonid Meteor Shower (LMS). The masses of the meteors are estimated to be in the range of 10^{-10}–10^{-5} g.

Keyword. Meteor—meteor shower—fragmentation.

1. Introduction

Every day, a large number of meteoroids ablate in the Earth's atmosphere. When the comet is around its perihelion, meteoroids are ejected by the comet as its frozen ices sublimate under the heat of the Sun. The momentum transfer of the gases expanding away from the nucleus must be enough to overcome the gravity of the nucleus for meteoroids to escape a comet (Whipple 1951). Both of these forces, gas drag and gravity, increase with the size of the nucleus assuming other parameters to be constant. The gas drag is more important except for large meteoroids or extremely big comets (Whipple 1951). The path of the meteoroid around the Sun is elliptical with the Sun at one of the foci. A meteoroid stream is formed when the ejected meteoroids complete one orbit around the Sun. Initially, meteoroids hang around the comet nucleus as a dust cloud, called the dust coma. Such meteoroids define a 'trail center' and the calculations tell us by how much the Earth misses this trail center. In reality, meteoroids are ejected over an arc of the parent comet's orbit, covering many months or even over a year, and over a range of directions from the comet nucleus; these effects result in the trail having a cross section (in the ecliptic plane) with a particular shape and characteristic width. Meteoroids accelerate at their closest approach at its perihelion and move slowly at their aphelion. Perturbations due to gravity result in changes in the orbit, orbital period and the time it takes to return after one orbit and is independent of the mass of the orbiting object. Hence, the meteoroid orbit is changed in much the same way as that of its comet's orbit. The less time the meteoroids

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spend in the neighborhood of Jupiter, less will be the perturbations in the orbit. The perturbations in orbit may cause a change in eccentricity of the orbit or its orientation by the gravity of the planets, especially Jupiter. If the trail were really to exist only at the trail center, it would be harder for the Earth to encounter any meteors. Of course, the perturbations are probable when the meteoroids are close to the Jupiter's orbit and the extent of perturbation depends on the position of Jupiter at that moment. As a result, the orbital changes are somewhat different for meteoroids (and comets) at different positions along the orbit. All meteoroids follow their independent orbit around the Sun, typically making a slightly wider orbit than the comet due to Poynting–Robertson effect and radiation pressure. As a result, they tend to come back later. It just takes longer to complete one orbit. Some particles take a lot longer, depending on the direction and speed of ejection and their size. A meteor shower occurs only when the meteoroids enter the Earth's atmosphere by crossing the ecliptic plane. The cross section defines the spatial distribution of meteoroids, and the Earth follows one path through this cross section. When the meteoroid arrives from the North, this point is called the "descending node" of the orbit. And when the meteoroid arrives from the South, it is called the "ascending node".

The comet 55P/Tempel-Tuttle having a periodicity of 33 years is the parent body of Leonid meteor shower, the radiant of the shower located in constellation Leo with its RA at 10h 08m and at declination of $+22^{\circ}$. The comet had its recent perihelion passage in February 1998. Osculating orbital elements for 55P/Tempel-Tuttle during their most recent perihelion passages is presented in Table 1 (a is the semi-major axis of the orbit in AU, e is the eccentricity, i is the inclination of the orbit from the ecliptic plane in degrees, Ω is the longitude of the ascending node in degrees, ω is the argument of perihelion in degrees, q is the perihelion distance in AU, r_{node} is the heliocentric distance of descending node in AU and T is the time of the most recent perihelion). The trail and stream cross sections have evolved with time (Ryabova 2003) owing to dispersive forces such as planetary perturbations or radiative forces. If not, meteor streams generally possess a considerable amount of fine structure which often takes the form of long, dense, narrow trails of dust and meteoroids (Asher 2000). Because they are narrow, the Earth may miss most of them when it passes through the stream. But when the Earth passes through a trail, a meteor outburst or storm occurs.

Our article is aimed to establish the meteoroid fragmentation as a reliable tool to evaluate the meteoroid stream structure. We are the first to study the stream structure in lines of fragmentation. The fragmentation study complements well the conclusions we drew based on distribution of echo durations and meteoroid mass distribution during the shower.

2. Observations

The MST Radar (13.5° N, 79.2° E) located at Gadanki, India is a powerful tool for making detailed observations of meteor echoes because of its high power narrow, near-vertical beams and high pulse repetition frequency. The system description and its technical functionality are well reported in Rao (1995). The specifications used for recording the meteor shower are listed in Table 2. The observations were recorded with four different beam orientations ($E_{20}, W_{20}, Z_x, N_{13}$, where the subscript 20 indicates 20° off Zenith angle and the subscript 13 indicates 13° off the Zenith angle. used for sporadic E produced during meteor shower). The experiment was conducted from 18:00 hours to 06:00 hours local time (LT) each night continuously during the shower days from 16th to 20th November 2010. The offline analysis of raw data for each night is done by separating the frames containing the meteor echo signatures, which exhibit a sharp increase in amplitude followed by decay.

3. Results and discussion

The nocturnal variation of meteoroid activity on all the observation days, i.e. from 16/17 November to 19/20 November for the year 2010 are presented in

Table 1. Orbital parameters of the comet 55P/Tempel-Tuttle during its recent perihelion.

Comet	a	e	i	Ω	ω	q	r_{node}	T
55P/Tempel-Tuttle	10.33	0.90553	162.5	235.26	172.5	0.97698	0.9806	02/28/1998

Table 2. Radar parameters for MST radar.

Frequency	53 MHz
Aperture area	16,900 m^2
Peak power	2 MW
Beam width	3°
Inter pulse period	1000 μs
Pulse width	8 ms
Altitude range	80–120 km

Figure 1. The zenithal hourly rate (ZHR) of occurrence of meteors on all the observation days plotted here are obtained by deducting the background count from the observed count. The activity prior to local midnight is not treated as the shower component. Shower activity began to increase from 16/17th November onwards. The specific peak on each observation day is registered in the early hours of dawn at 03:00–04:00 hr (LT) on 18/19 and 19/20 November and an hour before on 16/17 and 17/18 Nov. There was a gradual increase in ZHR from local midnight and it reached its maximum during the peak hours (03:00–04:00 hr (LT)) and then the activity decreased. This is a common trend which was observed on all the days of activity. As the Earth encountered meteors from East during dawn, the hourly rate was higher at that time when the radiant had risen above the horizon compared to the remaining hours of observation. The shower activity was low on 16/17 November and exhibited a consistent activity for the rest of the days. There was no outburst or sudden rise in activity on peak day, i.e. on 18/19th November, but it ensured moderately higher rates when compared to the pre- and post-peak days (i.e. 17/18 and 19/20 November). There was no sudden fall in activity on the last day of observation. The Earth dragged a large number of particles during the last two days of observation (i.e. 18/19 and 19/20 November). The Earth was at the outer periphery or sparse regions of the stream, and hence it encountered less and lighter meteoroids. On 18/19 November, the Earth might have entered the dense part of the stream, which helped in bagging rich number of massive meteoroids on that day when compared to the initial two days of observation. Similar activity continued on 19/20 November with a marginal decline. A 23 revolutions old stream left by the comet in the year 1234 AD caused this activity in the year 2010. Hence it is obvious to expect that the particles may not be as spatially dense as the younger streams, would be loosely packed and redistributed, and hence the activity might have spread over days around the peak

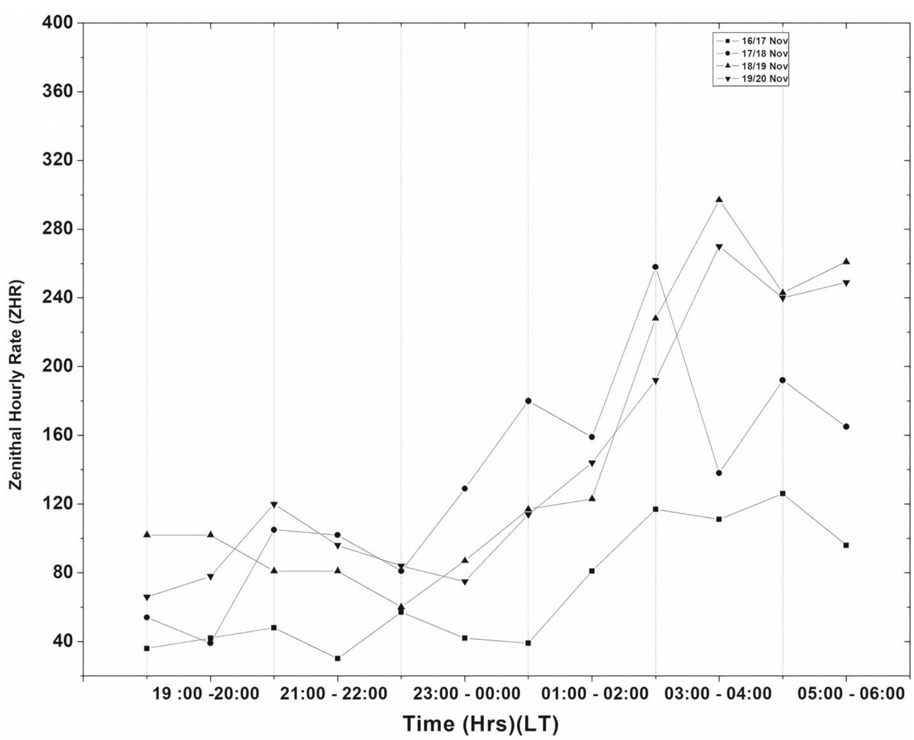

Figure 1. The nocturnal variation of the 2010 Leonid meteor shower.

activity day, which resulted in a broad peak rather than a narrow peak.

The encounter distance of the trails for the years 1996–2010 is presented in Table 3. The trail contributing to the maximum activity, encounter distances tabulated are retrieved from the works of McNaught and Asher (1999), Vaubaillon *et al*. (2005), Maslov (2007) and Meng (2005). The r_D and r_E (=0.9886 AU) are the heliocentric distances of the dust trail's descending node and of the Earth at the same longitude, $r_E - r_D$ gives the measure of the distance between the Earth and the centre of the trail. The quantity $r_D - r_E$ (encounter distance) is positive or negative when the Earth passes respectively inside or outside the centre of the trail relative to the Sun. The closer encounters have smaller values of $|r_E - r_D|$, the 3 revolutions-old trail was encountered at a miss distance of 0.0009 AU which is roughly ten times the Earth's diameter. Owing to the planetary perturbations, simple trail structures and multiple encounters with the same trails are possible as the trails become older, which is evident from Table 3. Each stream left behind by the comet is able to cause the activity for at least two years. This portraits the cross section of the stream, the perturbations, gravitational effects and also the Poynting–Robertson effect and radiation pressures on the streams.

When the comet passes close to Earth's orbit, such as in the case of the Leonids, there may be dust trail crossings from recently ejected dust. Multiple trails will exist and are slightly displaced from each other because of the evolution of the parent comet. As a result, more than one meteor storm can happen when Earth travels through the forest of trails. Meteoroid streams have simultaneously, but separately and closely existed, in which Earth has been wrapped up in the year 2007 (Rakesh Chandra *et al.* 2011) causing multiple peaks. Such peaks are not recorded in 2010 as it encountered solely a stream left behind in the year 1234 AD, which correspond to the 23rd apparition of the parent body.

4. Meteor activity based on echo duration

The meteor activity has been studied by classifying it into three categories based on the observed echo durations using MST radar (Simek & Mac Intosh 1986, 1989; Pecina & Pecinova 2004). The type I are very short duration echoes with durations less than 0.4 s, type – III are long duration echoes with durations greater than 0.8 s and type II echoes are short and transitional echoes having durations intermediate to type I and type III.

It has been observed from Table 4 that the greatest contribution to the shower is from very short duration echoes (type I) which approximates to 72% of the total activity, 18% is from short duration echoes (type II) and the rest is from longer duration echoes. The radar detected a good number of trail echoes, head echoes descending with high line-of-sight velocities and very few head echoes were found to be associated with trail echoes. The head echoes were undetectable in many frames as they lasted for very

Table 3. The encounter distance of the trails for the years 1996–2010.

Year	Trail contributing to maximum activity	$r_D - r_E$ (AU)
1996	1499, 1135	–0.00096, –0.00035
1997	1167	0.00048
1998	1965, 1932, 1866	–0.006659, –0.00535, –0.00386
1999	1899, 1932, 1965	0.00065, –0.00185, 0.00464
2000	1932, 1733, 1866	0.00116, –0.0007, –0.00079
2001	1767, 1866, 1965	0.00085, –0.00012, –0.0021
2002	1767, 1866, 1965	–0.00016, 0.0004, –0.00177
2003	1499, 1733	–0.00219, 0.00342
2004	1733	–0.00198
2005	1167	–0.00147
2006	1932	0.00013
2007	1932	0.00034
2008	1466	–0.00272
2009	1466, 1533	–0.00058, 0.00044
2010	1234	–0.00065

Table 4. Meteor activity distribution based on echo durations of the trails.

Date	Type	Time											
		18:00–19:00	19:00–20:00	20:00–21:00	21:00–22:00	22:00–23:00	23:00–00:00	00:00–01:00	01:00–02:00	02:00–03:00	03:00–04:00	04:00–05:00	05:00–06:00
16/17 November	I	4	5	6	5	8	13	10	15	25	25	27	22
	II	1	2	4	4	6	3	3	10	8	4	10	7
	III	1	1	2	2	4	3	2	3	5	5	5	3
17/18 November	I	18	11	31	21	19	36	53	44	59	33	46	47
	II	2	3	7	10	6	4	5	6	17	4	14	6
	III	2	2	2	3	2	3	2	4	7	9	4	2
18/19 November	I	28	29	20	17	16	15	30	24	57	63	57	64
	II	4	6	5	7	5	9	4	13	6	27	7	12
	III	2	2	3	2	2	4	5	5	12	7	15	9
19/20 November	I	20	21	23	23	18	18	27	39	36	48	38	61
	II	2	5	5	4	5	4	5	7	17	25	16	16
	III	2	2	2	3	3	2	4	3	10	17	15	7

short time and also they might have entered the null regions of the beam. Most of the long duration echoes were observed at lower heights, approximately below 100 km and this may be attributed to high background plasma density and slow diffusion rates due to collisions. Hence they exhibited longer durations at lower altitudes rather than at higher altitudes. The duration of long duration echoes registered over Gadanki (>0.8 s) were much shorter than long duration echoes observed at mid- and high-latitude station (Dyrud *et al.* 2011). Such short durations may be attributed to the aspect sensitivity of the radar, and also due to comparatively low background plasma densities during night times, enabling the trails to diffuse quickly (Dyrud *et al.* 2011). Further, the Leonids with declination angle of 22° N, high eccentricity and high entry velocities of 54 km s^{-1} to 72 km s^{-1} might have cumulatively added to the trails rapid diffusion.

From Table 4, we notice that there is a significant increase in the shower activity after midnight on each day of observation. Further, the activity was low on 16/17 November, and it began to rise from 17/18 November and reached its peak on 18/19 November and then again it decreased on 19/20 November. We can also observe that very short duration echoes were prevalent (type-I) during the shower. Even though there was a gradual increase in the number of type II echoes recorded as the shower progressed, their contribution was not huge and hardly few type III longer duration echoes were recorded during the shower. The heavier meteoroids created large plasma density gradients, hence they take longer time to diffuse into the background. Thus heavier meteoroids have longer durations when compared to lighter meteoroids. From Table 4, we can also infer that from 00:00 hr to 06:00 hr LT, the number of particles from all the classes are increasing gradually. Further, the number of type I particles increased till 18/19 November and then it decreased. On the same day, an increasing trend is observed in type II and type III class particles. Further, it was also observed that the peak activity occurred at 02:00–03:00 hr LT on 16/17 and 17/18 November, whereas on 18/19 and 19/20 November, it occurred at 03:00–04:00 hr LT respectively. As the age of the stream is very old for their particle reorganization to depend only on the points on the comet orbit where the meteoroids were released and the directions in which they were ejected, hence radiation pressure and Poynting–Robertson effect should also be considered for particle redistribution in the stream. Owing to

Table 5. Physical symbols and basic values used in the above model.

Symbol	Quantity/source	Value/source
dv/dt	Deceleration	–
dm/dt	Mass loss due to ablation	–
dT/dt	Temperature gradient	–
T	Temperature	–
T_0	Atmospheric temperature	150–170 K
A	Surface area	–
A_{cross}	Cross section area	–
β	Ionization efficiency	–
Λ_s	Sputtering efficiency	–
σ_{SB}	Stefan–Boltzmann constant	5.67×10^{-8} W/m^2 K^4
σ_a	Ablation parameter	10^{-8} s^2/m^2
C1	Constants (Hunt *et al.* 2003)	6.92×10^{11}kg m^{-2} s^{-1} K$^{-1/2}$
C2	Constants (Hunt *et al.* 2003)	57800–80000 K
C3	Constants (Hunt *et al.* 2003)	1×10^3J kg^{-1} K^{-1}
Q	Constants (Hunt *et al.* 2003)	7×10^3J s^{-1}
C	Heat capacity	0.8–0.95kJ g^{-1} K^{-1}
m	Meteor mass	10^{-6}–10^{-14} kg
m_a	Mass of ablated meteor species	4.98×10^{-26} kg
V	Meteor velocity	–
v_{thres}	Threshold velocity	5–8 km s^{-1}
C_d	Drag coefficient	0.2–1.17
M_r	Radio magnitude	–
ρ_{air}	Air density	Taken from MSIS00
ρ_{met}	Meteor density	1000–8000 kg/m^3
ϵ	Emission	0.5–0.95

these pressures, particles have redistributed among them such that the heavier particles are pushed away to the periphery of the streams and the lighter particles are pulled towards the Sun. With such particle redistribution within the stream, the Earth crossed the periphery of dust trail during the early days of shower (16/17 November) and hence encountered lighter particles first and then the heavier particles.

5. Estimation of meteoroid mass

The mass of the incoming meteoroid is estimated by following the model described by Stober and Jacobi (2008). By considering the processes of sputtering and evaporation of meteors in the meteor ablation model, the meteor mass has been estimated precisely. The threshold temperature of meteor ablation to occur is mentioned in Baggaley (2002) and is supported by Hill *et al.* (2005), while studying the high altitude meteors and a threshold energy for impinging molecules to start the process of sputtering has been found. The constants and physical symbols used in this model are presented in Table 5. In the three-equation model, these effects are included by a temperature-dependent sputtering efficiency given as

$$\Lambda_s = Q(6.10^{-16})e^{T/290}. \qquad (1)$$

The temperature gradient is given as

$$\frac{dT}{dt} = \frac{A_{\mathrm{cross}}\rho_{\mathrm{air}}v^3}{2C_3 m}(1-\Lambda_s) - \frac{\epsilon A \sigma_{\mathrm{SB}}(T^4 - T_0^4)}{C_3 m} - \frac{A_{\mathrm{cross}}C_1 Q}{mC_3 T^{1/2}} e^{\frac{-c_2}{T}}. \qquad (2)$$

The mass loss due to ablation is given as

$$\frac{dm}{dt} = \frac{-A_{\mathrm{cross}}c_d C_1}{T^{1/2}} e^{\frac{-c_2}{T}} - \frac{-\Lambda_s \rho_{\mathrm{air}} A_{\mathrm{cross}} v^3}{2Q}. \qquad (3)$$

Solving the equations enables us to calculate electron line density assuming (Jones 1997) ionization efficiency

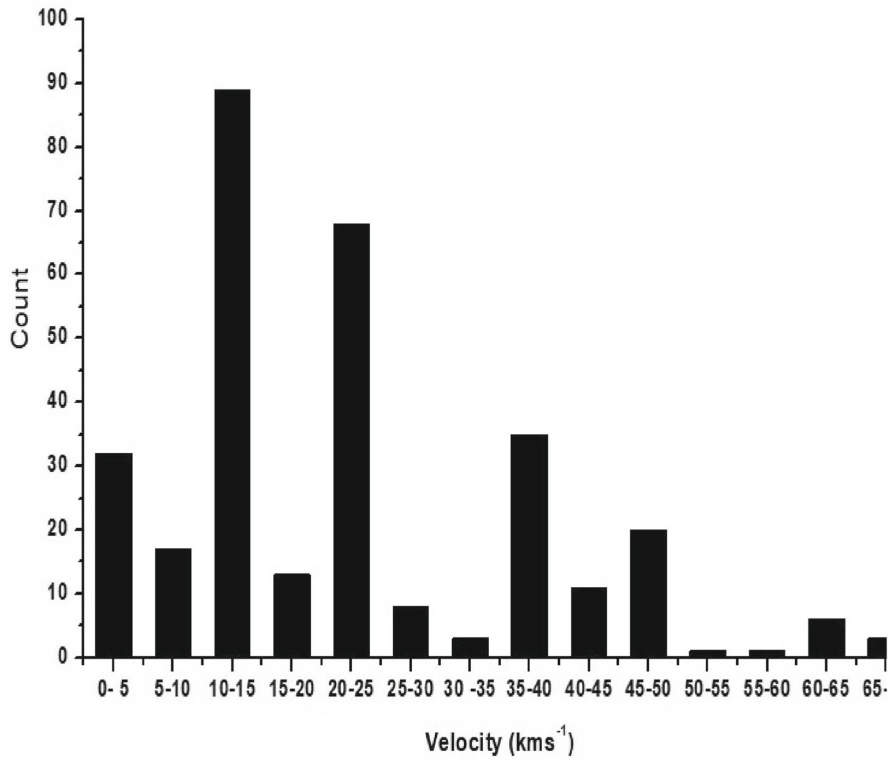

Figure 2. Log (mass/g) estimated during the Leonid meteor shower 2010.

$$\beta = 9.4 \times 10^{-6}(v - v_{\mathrm{thres}}) \cdot v^{0.8}, \tag{4}$$

where threshold velocity v_{thres} defines the velocity below which certain atom can no longer be ionized by impinging meteors. Using Jones (1997), the electron line density along the meteor flight path is given by

$$q = \frac{\beta}{m_{\mathrm{a}} v} \frac{\mathrm{d}m}{\mathrm{d}t}. \tag{5}$$

The three-equation model is thoroughly discussed in Stober and Jacobi (2008) by using the same equations. The meteor mass is estimated and the constants appearing in the above relations were suitably taken from MSIS00 model.

The range of the meteoroid mass is estimated to be in between 10^{-9}–10^{-5} g. As discussed in the earlier paragraphs, the massive meteors were pushed away in the stream and lighter particles were encountered first by the Earth. Massive meteors were observed in good number only lately. Figure 2 shows meteor mass distribution during the shower days, Logarithmic masses per gram of the meteors were plotted against their occurrence rate. The massive meteors are very sparse in number (this can be inferred from latter half of Figure 2) throughout the shower crediting the contribution of lighter meteors for the current shower in 2010.

Table 6. Percentage of fragmentation during LEONIDS 2010.

	Day		
Time	17/18	18/19	19/20
00:00–01:00	12.6	16.6	21.4
01:00–02:00	14.2	17.6	14.8
02:00–03:00	12.9	20.5	12.0
03:00–04:00	14.2	23.3	13.15
04:00–05:00	8.8	20.0	15.7
05:00–06:00	15.6	20.8	9.09

The meteor shower activity shoots up during the early hours of the day when the radiant rises above the horizon. Hence, to confine to shower meteoroids, we have considered the activity between 00:00–06:00 hr and calculated their mass and percentage of fragmentation.

Fragmentation is one of the major mass deposition mechanism for meteoroids. It is a mass dependent phenomenon. Janches *et al.* (2009) in their work on micro (gram) meteoroids had reported, based on their observations, that the major mass loss mechanism is ablation and differential ablation. It refers that for the

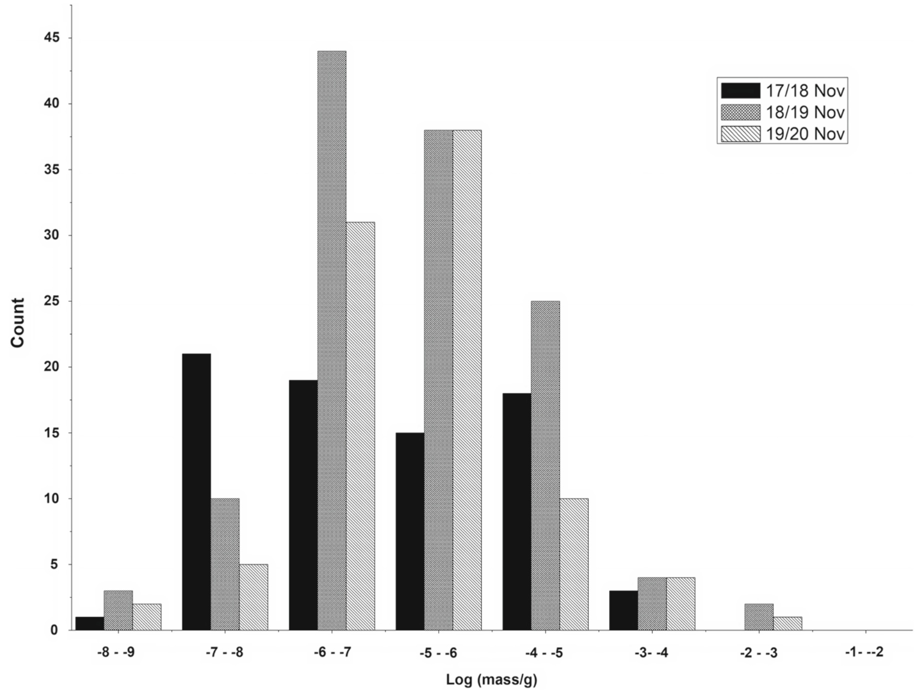

Figure 3. Distribution of meteor line-of-sight velocities.

masses above micro gram, fragmentation plays a vital role. The meteoroid signatures from raw data exhibiting longer durations are initially identified and then their masses are estimated (mass estimation is discussed in Section 5). The meteoroids whose masses are in microgram range are separated and analyzed further. An abrupt change in SNR is a clear signature of meteoroid fragmentation as meteoroids which are undergoing ablation have smooth decay. The observed line-of-sight velocities in each range bin exhibited the same trend as that of SNR which showed an abrupt change. From Table 6, we observe that percentage of fragmentation was found to increase from 00:00 hr and then reached a maximum between 03:00–04:00 hr, and then decreased again. This trend is observed on all the shower days. From Figure 2, we report here that the number of particles weighing less than 10^{-6} g are more during the shower and contribution to the shower by meteoroids of mass greater than 10^{-6} g is more on 18/19 November when compared to the other days. Also, from Table 6, we notice that the fragmentation percentage is more on 18/19 November when compared to the rest of the days. The highest fragmentation percentage was recorded on 18/19 November between 03:00–04:00 hr, indicating that on this day the Earth encountered heavier particles with masses greater than 10^{-6} g and might have undergone fragmentation. The percentage of fragmentation was low on pre-peak and post-peak days (17/18 and 19/20). This indicates that most of the meteoroids might have undergone ablation and differential ablation, whereas according to Janches *et al.* (2009) meteoroids whose masses are less than or equal to micro gram size are more prone to ablation and differential ablation. The percentage of fragmentation (Table 6) and the meteoroid mass (Figure 2) show the same, implying microgram-sized particles and still lower masses are unlikely to undergo fragmentation.

From the above discussion and from tabulated echo durations we may speculate that as the Earth passes through the streams one after the other, it encountered lighter particles first and then the heavier ones and again the lighter particles.The line-of-sight velocities of the incoming meteors is plotted against their occurrence rate and presented in Figure 3. Many meteors have not survived for more than two range bins which priced up to a good number of meteors having velocities in the range of 10–15 km s^{-1}. As the shower progressed, few meteors have descended enough to estimate their velocities in the range of 20–25 km s^{-1}. Some of these head echoes also created trails owing to the late phase of ablation. As the shower progressed, radar registered few meteors with high line-of-sight velocities which descended five to seven range bins in fractions of less than a half second. Such meteors have often undergone terminus ablation, which is quite interesting and is not the scope of this present paper, making it a point to be addressed for our future works.

6. Conclusions

It can be inferred from the above discussions that the activity of Leonid meteor shower in 2010 is primarily due to the lighter particles of the stream. The stream composition as understood from the distribution of echo duration and meteoroid mass is comprehensively substantiated with meteoroid fragmentation phenomenon. The activity is largely due to the particles of size 10^{-9} to 10^{-6} g. This is reasonable to justify that such trail composition with large dust cloud and few significant meteors may be obvious as the trail causing the shower in 2010 belongs to 23 revolutions old, aging approximately 770 years making it difficult to hold heavy particles in the stream. Also the old trails are not spatially dense, loosely packed and the activity has spread over days around the peak activity day. This resulted in a broad peak rather than a narrow peak. Orbital perturbations by Jupiter, and to a lesser extent by radiation pressure might have allowed for the differential redistribution of the particles within the stream.

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