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LETTER

Meteoroid Clusters in Leonids: Evidence of Fragmentation in Space

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Abstract

Three short-duration "outbursts", in which more than 20–40 meteors appeared in a few seconds, have been reported during a recent Leonid storm. The meteors in these events were extremely localized within a few hundred km, which should be caused by clusters of meteoroids. The existence of such clusters indicates the fragmentation of meteoroids during orbital motion in interplanetary space. Considering the extent of the spatial distribution, the fragmentation should have occurred at around the perihelion passage of the meteoroids just before encountering the Earth. This may cause a possible enhancement of smaller meteoroids, even in old dust trails. A possible example of similar clusters in the past meteor storm of Giacobinids is also noted.

Key words: interplanetary medium — meteoroids — meteors — meteor showers: individual (Leonids) — solar system

1. Introduction

In recent activities of the Leonids meteor storm, several trials for detecting a non-random grouping of meteors have been carried out (e.g. Toth et al. 2003). A non-random group, if any, should provide information about the history of the ejection of the meteoroids from the cometary nucleus, or on the orbital evolution of meteoroids in space. As extreme examples of non-random phenomena, several short-duration "outbursts" of meteors were reported concerning these activities of the Leonids. These outbursts are defined in this paper such that many meteors appeared simultaneously within a few seconds. The first example of such "outbursts" (hereafter, No. 97-1) was observed in 1997 Leonids, in which 100–150 meteors appeared within only two seconds (Kinoshita et al. 1999). New examples were reported in a 2001 Leonid storm over Japan. One occurred at 17h 56m 22s UT on November 18 (hereafter, No. 02-1), in which at least 15 meteors appeared within four seconds (Watanabe et al. 2002). Another outburst was recorded at 18h 29m 21s UT on November 18 (hereafter, No. 02-2), in which 38 meteors appeared within two seconds (Watanabe et al. 2003). These "outbursts" should be due to clusters of meteoroids. In this paper, the characteristics of the observed meteoroid clusters are summarized, and the origin of such clusters is discussed.

2. Characteristics of the Clusters Observed in Leonids

The characteristics of the observed clusters in Leonids are summarized in table 1. While all of the phenomena were recorded by a wide-field video camera system, the spatial extent of the meteors was extremely localized within an order of 100 km. The first example, No. 97-1, was recorded by a high-sensitivity camera system which consisted of an image intensifier (type V3287P, Hamamatsu Co.) together with a 35-mm camera lens (f = 24 mm, F1.4, Canon Co.), which

Table 1. Summary of meteoroid clusters observed so far in Leonids.

Designation No.	Epoch (UT)	Duration (s)	No. meteors	Spatial extent (km) ‖Orbit	⊥Orbit	Reference
97-1	13h 31m 51s 1997 November 17	2	100–150	100	50	Kinoshita et al. (1999)
02-1	17h 56m 22s 2002 November 18	2	≥ 15	⋯	⋯	Watanabe et al. (2002)
02-2	18h 29m 21s 2002 November 18	2	38	150–200	100	Watanabe et al. (2003)

provided a field of view of 55° ϕ. Kinoshita et al. (1999) derived the spatial extent of the meteors in the orbit as 100 km along the trajectory and 50 km in the lateral direction. The other two examples in 2001 Leonids were also recorded by a wide-field system consisting of a monochromatic CCD camera (WATEC Co., type WAT-100N) together with a CS-mount camera lens (f = 3.8 mm, F0.8, CBC Co.). This system realized a field of view of 80.°6 × 65.°0 with a limiting magnitude of about 4. Watanabe et al. (2003) shows a detailed analysis of the outburst No. 02-2, and reconstructed the space distribution of the meteoroids just before their entering the Earth's atmosphere based on the time and position of each meteor. The derived spatial extent was also on the order of 100 km. They are distributed not spherically, but rather elongated up to 150–200 km along the direction of the radiant point, namely almost along the orbit. Although a similar analysis for No. 02-1 has not been performed, because they appeared at the edge of the field, a rough estimate of the spatial distribution is similar to No. 02-2. As far as the examples known so far, the spatial extent of the clusters is extremely localized to be an order of 100 km with some widened distribution along the orbit.

The brightness distribution is not so unusual (Watanabe et al. 2003). However, it should be noted that in two examples one bright meteor appeared in each outburst. Kinoshita et al. (1999) wrote that many faint meteors appeared after the apparition of a bright meteor with a magnitude of −2. In outburst No. 02-1 in the 2001 Leonids, the magnitude of the brightest meteor was estimated to be −3, and those of other meteors were fainter than −1. On the other hand, there were not very extreme bright meteors in the outburst of No. 02-2. It is difficult to say anything about the existence of a large meteoroid in the clusters due to a lack of samples. It should be noted that the apparition of meteors fainter than 4th magnitude have been reported for No. 02-1 based on a telescopic video observation (Shiki et al. 2003). The magnitude distribution should be discussed by combining such data on much fainter meteors.

3. Origin of Meteoroid Clusters

The localized distribution within an order of 100 km is a clue to the origin of the clusters. We insist that such clusters are produced by the fragmentations of large meteoroids based on the reasons described in the following subsections, where we try to clarify the epoch of the fragmentations.

3.1. *At or Near Ejection?*

It is easily shown that these clusters did not originate at the ejection, nor were they formed by fragmentation near to the ejection. Consider that they are ejected as clusters directly from a cometary nucleus. Because the activity of the parent comet 55P/Tempel–Tuttle depends strongly on the heliocentric distance (Watanabe et al. 2001), the meteoroids' ejection are thought to be near the perihelion. If we assume that a certain cluster was ejected at around the perihelion passage in 1965, the difference in the arrival time of the meteoroids after one revolution is roughly on the order of $dT = 17.6 \times dv$ (days), where dv is the relative velocity of each meteoroid in $\mathrm{m\,s^{-1}}$ (Kozai 2002). For keeping meteoroids within a time difference of a few seconds, we need an extremely small relative velocity, such as $0.003\,\mathrm{mm\ s^{-1}}$. This is an unreasonably small value. The same logic can be applied in a case such that the meteoroids experience fragmentation just after the ejection from the cometary nucleus. The morphology of the dust tail, such as striae, indicates definite evidence of fragmentation of the dust particles just after ejection from the nuclei. The coma morphology observed from ground-based observations also suggests fragmentation near the nucleus (Combi 1994). In-situ measurements of the smaller dust particles near the nucleus by the spacecrafts also indicate possible fragmentation (Keller et al. 1990). Hence, it is natural to assume fragmentations near the ejection. However, we also need an extremely small relative velocity among the meteoroids.

The observed clusters in 2001 Leonids are believed to be located within the old trails of 4 or 9 revolutions (McNaught, Asher 1999). Therefore, the meteoroids in these clusters are considered to have been ejected in 1866 or in 1699; thus the required relative velocity should be much smaller than the above value. Moreover, we neglect the effect of the direction of the ejection and the radiation pressure here, much smaller relative velocity should be derived when we apply the exact formula, which takes these effects into account based on the relation between the relative velocity and the period change, such as equation (23) given by Ma et al. (2001). In any case, the derived values are too small to be real space. The ejection velocity of the meteoroids are usually an order of at most 5–20 $\mathrm{m\,s^{-1}}$. Considering the random fluctuation of the energy deposit to the velocity at ejection, the expected relative velocity should be on the order of 30 $\mathrm{cm\,s^{-1}}$, which is much larger than the required relative velocity.

We conclude that such meteoroid clusters were not ejected directly as clusters from a cometary nucleus, nor formed by fragmentation near the ejection.

3.2. *Just before Entry?*

The second idea is that it occurred just before entering into the Earth. The meteoroids are thought to be charged up at a certain level in interplanetary space (Kimura, Mann 1998). The electric force caused by a rapid change in the circumstances by entering the Earth's magnetosphere may be able to disrupt the meteoroids. However, this is also unlikely due to the requirement of a large relative velocity for realizing the observed space dimension. If a meteoroid is assumed to be fragmented at the boundary of the Earth's magnetosphere ($\sim 30 R_{\rm e}$), the required relative velocity of the meteoroids is on the order of $40\,{\rm m\,s^{-1}}$ in order to reproduce the spatial extent of the meteoroids in the cluster. This value is too large. Although the tidal force at the incoming orbit to the Earth is also one of the candidates, the relative velocity should be much smaller.

3.3. *At Perihelion?*

After all, fragmentation should have occurred at a certain epoch, which is long enough after ejection from the nucleus, and is also an appropriate time before entering the Earth. It is natural to consider the perihelion passage, because it is a special place for meteoroids where they will be strongly heated by solar insolation. Assume that a meteoroid is fragmented at the perihelion passage just before encountering the Earth. Due to the retrograde orbit, it takes only about 6 days to reach the Earth. Then, the required relative velocity to reproduce the observed spatial extent is about 20–50 $\rm cm\,s^{-1}$. This is a moderate value for the relative velocity for the fragments of meteoroids.

Although it is difficult to estimate the exact relative velocity without knowing the fragmentation mechanism, it is roughly thought to be the result of energy partition from the rotation of a mother meteoroid. The rotation of the mother meteoroid should be a result of energy partition when it was ejected from the cometary nucleus. According to collision experiments, the energy partition into translational and rotational motion at the ejection is thought to be 100 to 1 (Fujiwara 1987). When we assume the translational (ejection) velocity as being an order of $10\,{\rm m\,s^{-1}}$ for a spherical meteoroid of 1cm-radius (Asher, Emel'yanenko 2002), the expected rotation rate is an order of 0.1 s. At fragmentation, most of this rotation velocity should be deposited to the translational (relative) velocity of the fragments. Therefore, the relative velocity of the fragments should be an order of $1\,{\rm m\,s^{-1}}$, which is close to that required velocity derived from the assumption in this subsection. Therefore, the fragmentation of the meteoroid is thought to have occurred at around the perihelion passage just before entering the Earth.

4. Discussion

We concluded that the observed clusters of meteors are evidence of the fragmentations of meteoroids during their orbital motion, probably at around the perihelion passage just before encountering the Earth. The fragmentation of small bodies in the solar system is a well-known phenomenon for various objects over a wide range, from cometary nuclei (e.g. Comet C/1999 S4 LINEAR, Weaver et al. 2001) through cometary dust particles (e.g. striae in the dust tail of Comet C/1995 O1 Hale–Bopp, Watanabe et al. 1997). The latter case is well explained by the fragmentation-related model (Sekanina, Farrel 1980; Nishioka, Watanabe 1990). The size of meteoroids is thought to be on the order of 1 cm, which is between the size of the cometary nuclei and of the cometary dust particles. There is no reason to deny the possibilities of the fragmentation of meteoroids.

However, the mechanism of the fragmentation is still unknown. The most possible mechanism is a thermal effect at the perihelion. Each meteoroid comes to the perihelion about every 33 years, when volatile material, such as organic compounds, may partially evaporate. These volatile species may play an important role in bonding the refractory particles in a meteoroid as the glue such as those in cometary nuclei (Samarasinha 2001). Then, the clusters may be abundant in young meteor trails. Until now, there has been no report on such concentrated clusters in the 2001 Leonid storm over U.S. due to the 1766 trail. The cluster phenomena which we observed may possibly be within the younger 1866 trail. This may be indirect evidence of the importance of thermal effect for these phenomena.

Other mechanism, such as collisional disruption, should be considered for cometary nuclei, or asteroids. However, the collision cross section between meteoroids is too small to be considered, even in the dense part of the trails of the storm level. We may be able to neglect this possibility for the origin of the observed clusters in Leonids.

One of the common properties for three events is the non-isotropic spatial distribution of cluster meteoroids. It may be due to the Earth's perturbation, or to the orbital alignment of the meteoroids by the orbital evolution, or to a non-isotropic disruption such as a tidal effect. However, a simple dynamical consideration of all these idea failed to reproduce the non-isotropic distribution. A more comprehensive analysis should be done on the observed clusters including much fainter meteors.

The existence of meteoroid clusters should have a strong influence on the size distribution of the meteoroids. Although we do not know how much meteoroids experience such fragmentations, the evolution of the size distribution of the meteoroids should be affected at a certain level. The important aspect of this effect is to change the brightness distribution of the meteors in the trails. When a certain rate of the fragmentations is assumed, the brightness distribution should be bimodal due to an enhancement of smaller meteoroids produced by the fragmentation. In fact, the bimodality has been reported, as shown in table 2, on the magnitude distribution in 2001 storm by Suzuki (2002), who observed 159 Leonid meteors from 15h30m through 19h30m on November 19 via his video-camera system. It consists of an Image Intensifier (type V3287P, Hamamatsu Co.) together with a 35-mm camera lens (f = 85 mm, F1.2), provided the field of view as $13^\circ \times 10^\circ$ along with the limiting magnitude of 9. Comparing with the sporadic meteors, the bimodality of the magnitude distribution of the Leonids is clear. The enhancement of faint meteors is also

Table 2. Bimodal magnitude distribution derived from the video observation made by S. Suzuki (2002) during the 2001 Leonid storm over Japan.

Mag.	0	1	2	3	4	5	6	7	8	9	Total no.
Leo	2	8	20	23	21	15	12	28	25	4	159
Non-Leo	0	0	0	1	7	8	30	60	55	4	165

supported by several telescopic observations in 2001 Leonids (e.g. Nishiura et al. 2002). Such bimodality may be due to the effect of fragmentation or to the effect of a composite of two different dust trails.

Another important suggestion should be noted concerning the dust cloud detected in 1998 Leonid. Nakamura et al. (2000) succeeded to detect a reflection signal from meteoroids as a dust cloud of the 1998 Leonids at close to the radiant point. The radius of the trail, deduced from the spatial extent of the cloud, is approximately 0.01 AU, which is consistent with the spatial extent mapped out by historic accounts of meteor storms. The brightness of the cloud is approximately 2 to 3 percent of the background zodiacal light, and it should be noted that such brightness cannot be explained by simple model calculations based on the zenith hourly rate and population index of the meteor stream in 1998. However, if the small particles are abundant at this observation due to the fragmentation products, it may be possible to explain this cloud detection because smaller dust particles should effectively contribute to the reflection brightness due to the large number. A quantitative discussion will be presented after a detailed analysis of the data on the fainter meteors in the clusters together with the frequency.

It would be interesting to look for samples of clusters having another level of the spatial concentration. It is sometimes said that meteor apparitions are not random. There may be more spread “clusters” which may not be recognized as clusters until now. There is an indication for the existence of wide-spread clusters among the video data collected by the Astro-HS project (Suzuki et al. 2002).

It is not clear if these clusters are rare or if we could not notice these clusters by naked-eye observations. For all of the clusters discussed in this paper, no one noticed “outbursts” by naked-eye in real time, and they were all found by inspecting the recorded video tapes. We may not be able to recognize many meteors simultaneously due to the possible attention just to a few brighter meteors. On the other hand, we also note a possible similar example of such clusters in the past meteor storm of Giacobinids. In 1933 Giacobinids, Milligan (1934) wrote “At one time … as many as 100 might have been seen in any 5 seconds of time”. While the expression is slightly different from those of the clusters discussed so far, it may have been a similar cluster phenomenon.

Further analysis will be necessary for clarifying the nature of the meteoroid clusters among the data taken in 2002 Leonids.

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