

Optical Imaging of the Radiant Points of Leonids during the 2001 Storm with the 105 cm Kiso Schmidt Telescope

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Abstract

We report on the results of CCD imaging of the radiant points of Leonids with the 105 cm Kiso Schmidt telescope during its storm in 2001. The center coordinates of the observed field were $\alpha(\text{J2000.0}) = 10^{\text{h}}17^{\text{m}}02^{\text{s}}.4$ and $\delta(\text{J2000.0}) = +21^{\circ}37'48''.0$, corresponding to the center position between the two radiant points originating from dust trails created by the 1699 and 1866 returns of the Comet 55P/Tempel–Tuttle (McNaught, Asher 2001; WGN, 29, 156). Six CCD images having a field of view of $51'2 \times 51'2$ were obtained successively from 16h 58m to 18h 28m on November 18 (UT) in order to cover the two expected peaks of activity of the distinct radiant points. A limiting surface brightness of $25.93 \text{ mag arcsec}^{-2}$, i.e., the 1σ noise level of the sky background, was achieved in each image. As a result, we detected only one faint Leonid meteor which most likely originated from a dust trail created by the 1866 return. The integrated total magnitude of the meteor is $m_V = 18.34 \pm 0.34 \text{ mag}$ on the image. Assuming a duration time of 0.1–1 s, we estimate the magnitude at the maximum luminosity of this meteor to be $9.70 \pm 1.59 \text{ mag}$. This corresponds to a photometric mass of $(2.65^{+13.5}_{-2.22}) \times 10^{-10} \text{ kg}$, which makes this meteor one of the faintest and smallest Leonids detected so far.

Key words: comets: individual (Comet 55P/Tempel–Tuttle) — meteors, meteoroids

1. Introduction

The Leonids is one of the most famous and the most active meteor showers. Its strong meteor activity occurs every ~ 33 years, corresponding to the orbital period of the parent comet, 55P/Tempel–Tuttle. The strong meteor storm has been recorded since AD 902 (Mason 1995).

Meteor streams originate from small dust particles ejected by the parent comets. The dust particles form tubular structures along the orbits of the comets, which are called *Dust trails*. Every time a comet returns, a new dust trail forms along an orbit slightly shifted from the previous path due to gravitational perturbation. The size distribution of dust in the trails has been of particular interest, because it should be relevant to the formation and evolution of the dust trails. In fact, a large variation of the dust size has been reported. Sykes and Walker (1992) reported a number of dust trails associated with some meteor streams in the database of the Infrared Astronomical Satellite (IRAS). They estimated that the dust size is on the mm-scale. On the other hand, based on observations using the Infrared Space Observatory (ISO), Reach et al. (2000) suggested that the size of the dust particles in the trails originating from the Comet 2P/Encke is on the cm-scale. Furthermore, Nakamura et al. (2000) discovered a faint glow of scattered sunlight from the Leonid dust trail formed by Comet 55P/Tempel–Tuttle. According to their calculations, the dust contributing to the observed glow is likely to have a size of $\sim 10 \mu\text{m}$. The Leonids is a *young* meteor stream, and is therefore an important sample

to understand an early stage of the dynamical evolution of dust trails.

Although a direct measurement of the size distribution is hard to obtain, it is rather easy to determine the magnitude distributions of the meteor streams. In 1996, the population index, r , of Leonids was reported to be in the range of 1.6–1.9 (Arlt et al. 1996; Langbroek 1996a; Brown, Arlt 1997). In addition, Langbroek (1996a) found $r = 3.4$ for Leonid meteors with magnitudes brighter than $+1 \text{ mag}$. In Leonids 1997, Arlt and Brown (1998) obtained $r = 2.0$ – 2.5 . Jenniskens et al. (2000) found $r = 1.6$ for fireballs with magnitudes brighter than -1.5 mag with the Midcourse Space Experiment Satellite. For Leonids 1998, based on video camera component observations, Jenniskens (1999) found $r = 1.5$ for a wide component and $r = 1.8$ for narrow one. Arlt (1998a) also found $r = 1.19$ – 2.00 . In 1999, using a video camera, Molau et al. (1999a,b) found that the bright Leonid meteors in the range $0 \leq m_V \leq +2 \text{ mag}$ follow a power-law distribution with a population index of $r \sim 3.0$, which decreases down to $r \leq 2.0$ at a higher magnitude ($m_V \simeq 3 \text{ mag}$). They also found a turnover in the magnitude distribution, and suggested a very poor population of Leonids fainter than $+5 \text{ mag}$. Gural and Jenniskens (2000) obtained $r = 1.8$ from their observations with a video camera and a CCD camera. Arlt et al. (1999b) studied the Leonid activity based on data gathered from 434 observers, and also found an unusual magnitude distribution with a lack of both very bright and very faint meteors. These results indicate that the population index of the Leonid stream is smaller than

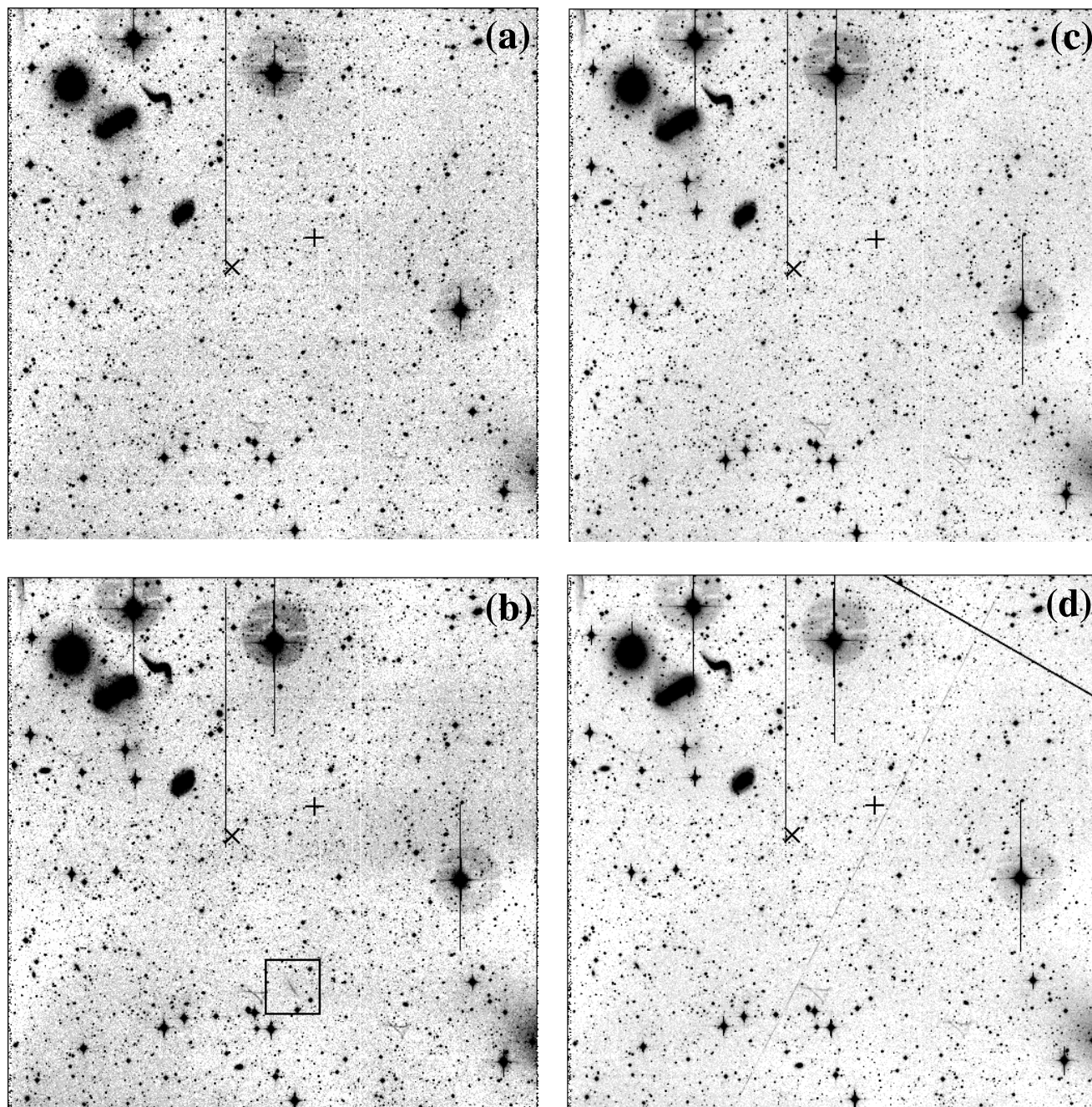


Fig. 1. V-band images of the region around the two radiant points of Leonids 2001. Panels from (a) to (f) correspond to the figure numbers from 1 to 6 in table 1 in this order. The plus and cross indicate the radiant points of the 1699 and 1866 returns of the parent comet, respectively. The box in panel (b) denotes the faint meteor detected by our observations (see figure 2a). The vertical black and white lines in each image are dead and saturated pixel columns, respectively. The image size is $51\frac{1}{2} \times 51\frac{1}{2}$. North is up and east is left.

those of other meteor streams, such as $r = 2.7$ of eta-Aquarids (Rendtel 1997), 2.2–3.1 of June Bootids (Rendtel et al. 1998; Hashimoto, Osada 1998; Arlt et al. 1999a; Arlt 2000), 2.55 of alpha-Cygnids (Olech et al. 1999), 2.7–3.0 of Draconids (Arlt 1998b; Langbroek 1996b), 1.85–2.75 of Geminids (Rendtel 2000), 2.9 of Lyrids (Porubčam, Štohl 1983), 2.36 of alpha-Monocerotids (Rendtel et al. 1996), and ~ 2 of Perseids (Arlt, Rendtel 1997; Rendtel, Arlt 1999; Arlt, Händel 2000; Olech 2000; Beech, Illingworth 2001). Because of the short time-scale of meteor phenomena and their faint surface brightness,

the cutoff magnitudes of any meteor streams are still unknown. For Leonids 1999, Pawlowski et al. (2001) attempted to detect very faint meteors using a 3 m liquid-mirror telescope located near Cloudcroft, New Mexico, USA. They, however, could not detect any Leonid meteors, but only sporadic ones. This is probably because Leonids was less active in 1999 when observable from the USA.

In 2001, the Leonids had been expected to show the strongest meteor activity for these several decades. Many studies predicted that Japan would be the best observational

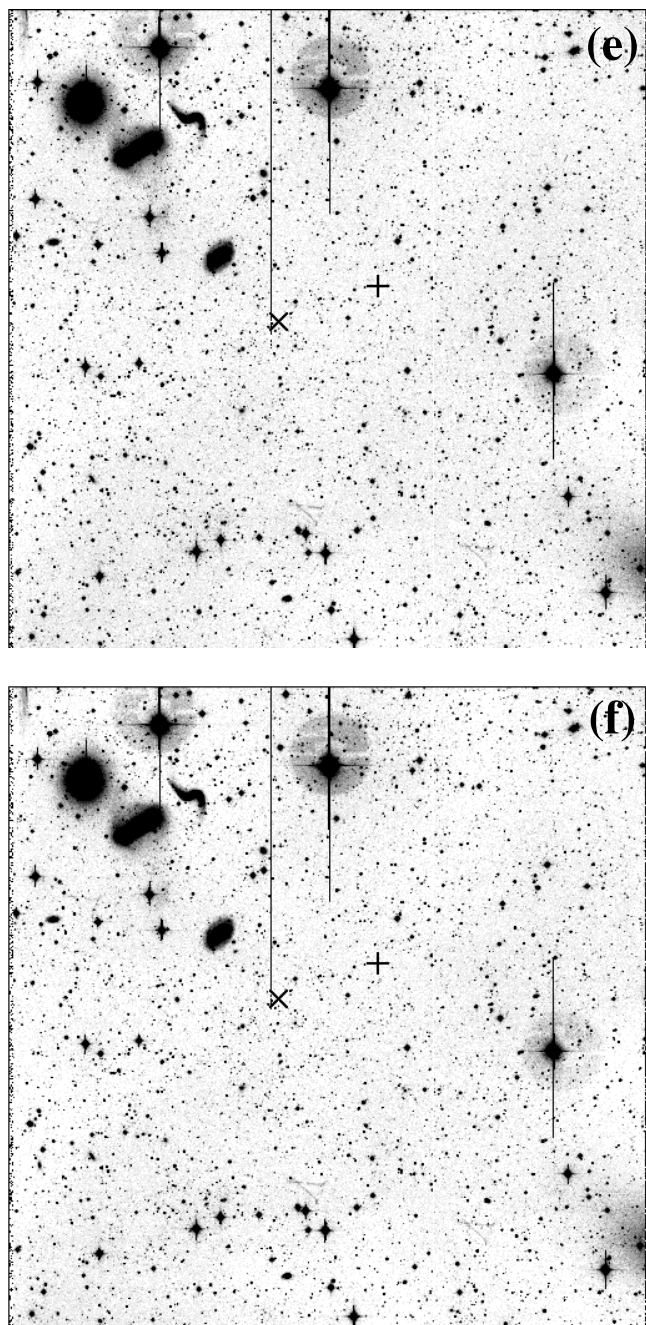


Fig. 1. (Continued.)

site for the Leonids in 2001, which should be most active from 17h 00m and 18h 30m on November 18 (UT) (Lyytinen, van Flandern 1999; McNaught, Asher 1999, 2001; Jenniskens 2001; Lyytinen et al. 2001). Especially, in 2001, the Earth was to pass through the two major dust trails within one hour, which were formed by returns of the Comet 55P/Tempel–Tuttle in 1699 and 1866. McNaught and Asher (2001) calculated the coordinates of the two radiant points to be $\alpha(\text{J2000.0}) = 10^{\text{h}}16^{\text{m}}43^{\text{s}}.2$, $\delta(\text{J2000.0}) = +21^{\circ}39'00''$ and $\alpha(\text{J2000.0}) = 10^{\text{h}}17^{\text{m}}19^{\text{s}}.2$, $\delta(\text{J2000.0}) = +21^{\circ}36'00''$; they predicted that the meteor showers from these radiant points should be most active at 17h 24m and 18h 13m on November 18 (UT), respectively.

Table 1. Journal of Observations.

Figure number	Starting time (UT: 2001 Nov. 18)	Exposure time (s)	Zenith distance
1	16h 58m	300	$57^{\circ}1$
2	17h 04m	900	$53^{\circ}9$
3	17h 21m	900	$50^{\circ}4$
4	17h 38m	900	$46^{\circ}9$
5	17h 55m	900	$43^{\circ}4$
6	18h 13m	900	$40^{\circ}0$

The purposes of our observations were 1) to distinguish the two radiant points, and 2) to probe into the cutoff in the magnitude distribution of meteors at the fainter end.

2. Observations

We carried out V-band imaging of the two radiant points of Leonids using a 2 K (2048×2048)-CCD camera attached to the prime focus of the 105 cm Schmidt telescope at Kiso Observatory [$137^{\circ}37'42''.2(\text{E})$, $+35^{\circ}47'38''.7(\text{N})$, 1130 m], belonging to the University of Tokyo, on 2001 November 18. The center coordinates of the observed field were set to $\alpha(\text{J2000.0}) = 10^{\text{h}}17^{\text{m}}02^{\text{s}}.4$ and $\delta(\text{J2000.0}) = +21^{\circ}37'48''.0$, which were tracked using an auto-guiding system during the observations. In Tokyo, Japan, this was the center position between the two radiant points of dust trails created around the 1699 and 1866 returns of the Comet 55P/Tempel–Tuttle (McNaught, Asher 2001). The camera provided a wide field of view ($51'.2 \times 51'.2$) with a pixel size of $1''.5$ on the sky. Although the observatory is located in Kiso, Nagano, the difference in the coordinates of the radiant points calculated for Tokyo and Kiso was very small compared to the field of view of the 2 K-CCD camera. The difference in the UT time for the peak of activity was also quite small between Tokyo and Kiso. Our observations were performed during the peak activity time predicted by McNaught and Asher (2001). The integration time for the first image was set at 300 s to confirm the field position, and then 5 other images were obtained successively with a 900 s integration time. The seeing was $\simeq 3''.1$ during the observations. Data reduction was performed in a standard way using IRAF.¹ We used the SPIRAL package (Hamabe, Ichikawa 1992) for sky background subtraction. A simple flux calibration was made by referring to five stars near the radiant points, USNO A2.0 1050-06242759, -06244184, -06244375, -06245748, -06246605 (Monet et al. 1998), and by using an empirical relationship found among the USNO B_p -, R_p -, and the Johnson V-magnitude,

$$V = 0.222 + 1.010 \times [B_p - 0.832 \times (B_p - R_p)]. \quad (1)$$

The calibration error was ± 0.34 mag for each image. A limiting surface brightness of ~ 25.93 mag arcsec $^{-2}$ was achieved, i.e., a 1σ noise level of the sky background. We summarize

¹ Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

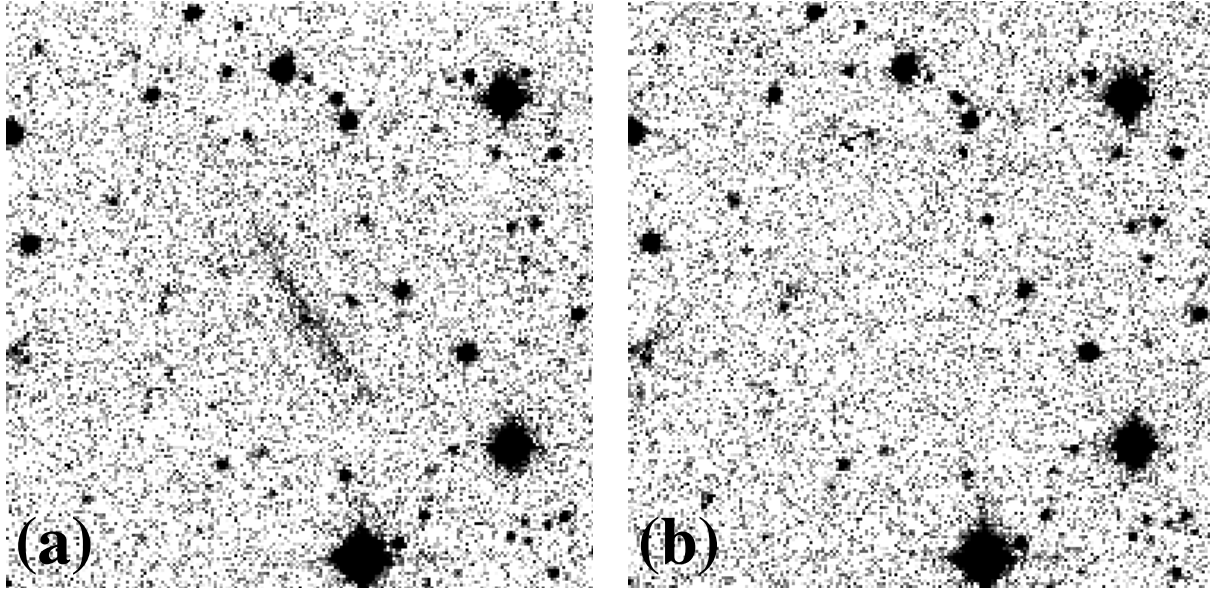


Fig. 2. a) The very faint meteor of Leonids 2001 detected in figure 1b shown on a finer scale. b) The same area as in figure 2a, but taken from figure 1c.

the observational parameters in table 1, and display all of the images obtained in figure 1.

3. Results

At first, we searched for meteors in our six images by eye inspection, but found no bright meteor in all of the images. We, however, found only one very faint meteor-like object, as shown in figure 1b. The smooth appearance of this object indicates that it should not be the track of a cosmic-ray (see figure 2a). In addition, because we cannot identify the same object in other frames (figure 2b), this should not be due to ghost light either. It is noteworthy that the direction of the elongation of this object points toward the radiant point of the 1866 returning, strongly indicating their relation. We therefore conclude that this object is a real meteor originating from the 1866 dust trail.

Using the SKYCAT/GAIA² package, we estimate the total intensity of this object to be enclosed within an ellipse with a semi-major axis of $67''.2$, an eccentricity of 0.98, and a position angle measured to the north of 57.0° . The resulting V magnitude is 18.34 ± 0.34 mag. This indicates that the meteor was quite faint, having a magnitude at the maximum luminosity of $m_V = 8.45\text{--}10.95$ mag (9.70 mag on the average), if we assume its duration time to be 0.1–1.0 s. The meteor is one of the faintest in Leonids detected so far.

4. Discussion

Within the 4800 s integration time in total, we detected only one meteor around the two activity peaks predicted in some literature. We estimated the photometric mass of the faint Leonid

Table 2. Magnitude Distribution of the Leonids in 2001.

Magnitudes (mag)	Number	Flux ($\text{km}^{-2} \text{s}^{-1}$)
$< -7 \pm 0.5$	1	$(1.96 \pm 1.96) \times 10^{-8*}$
-6 ± 0.5	2	$(3.92 \pm 2.77) \times 10^{-8*}$
-5 ± 0.5	3	$(5.88 \pm 3.39) \times 10^{-8*}$
-4 ± 0.5	14	$(2.74 \pm 0.73) \times 10^{-7*}$
-3 ± 0.5	37	$(7.25 \pm 1.19) \times 10^{-7*}$
-2 ± 0.5	60	$(1.18 \pm 0.15) \times 10^{-6*}$
-1 ± 0.5	110	$(2.15 \pm 0.21) \times 10^{-6*}$
0 ± 0.5	155	$(3.04 \pm 0.24) \times 10^{-6*}$
$+1 \pm 0.5$	176	$(3.45 \pm 2.60) \times 10^{-6*}$
$+2 \pm 0.5$	150	$(2.94 \pm 0.24) \times 10^{-6*}$
$+3 \pm 0.5$	161	$(3.15 \pm 0.25) \times 10^{-6*}$
$+9.70 \pm 1.59$	1	$(2.94 \pm 2.94) \times 10^{-5\dagger}$

* Data quoted from Watanabe et al. (2002).

† Present work.

meteor detected in our observations using the following mass–magnitude relation quoted from Pawlowski et al. (2001):

$$\log(m) = -4.68 + 0.495 \times \log[\cos(z)] - 0.495M, \quad (2)$$

where m is the photometric mass in kg, z is the meteor zenith distance, and M is the magnitude at the maximum luminosity determined by naked eyes. Disregarding a slight difference between M and the Johnson- V magnitude, m_V , which we used in this work, and substituting $M = m_V = 9.70 \pm 1.59$ mag and $z = 50^\circ$ into the equation, we estimated the photometric mass of the faint Leonid meteor to be $(2.65^{+13.5}_{-2.22}) \times 10^{-10}$ kg. The error of the meteor magnitude, ± 1.59 , is for an uncertainty in the duration time (0.1–1.0 s) as well as in the calibration. Assuming a spherical shape and a density of 1 g cm^{-3} , the mass derived here indicates a very small meteor having a size of $65.9^{+79.9}_{-61.6} \mu\text{m}$.

² SKYCAT is a tool that combines the visualization of images and access to catalogs and archive data for astronomy provided by ESO. GAIA is an image display and analysis tool that adds many photometry-related features to SKYCAT.

A few $\times 10 \mu\text{m}$ is comparable to those of the dust grains responsible for the zodiacal light, and is much smaller than other Leonid meteors reported to date. If the small meteor detected in our observations really originates from the dust trail created by the 1866 return of the Comet 55P/Tempel–Tuttle, it must have survived in the dust trail for at least $\geq 1.3 \times 10^2 \text{ yr}$. A question which immediately arises is what kept the small meteor in the dust trail for such a long time, because small dust of this size can easily disperse spontaneously or can be blown away by the radiation pressure and the solar wind. This remains an open problem at the moment. We, however, should note a simple possibility that the small meteor might be one of the fragments of a larger meteor that broke when or just before falling onto the earth. It is also possible that we highly underestimate the meteor mass, because the mass–magnitude relation which we adopted was originally established for a brighter magnitude range ($0.5 \leq M \leq 8.5 \text{ mag}$; Pawlowski et al. 2001), which might be erroneous for a faint meteor with $m_V = 9.70 \text{ mag}$.

The magnitude distribution of Leonids is of particular interest. Watanabe et al. (2002) investigated the magnitude distribution of Leonids in 2001 over the magnitude range from -7 to $+3 \text{ mag}$, and found that the meteor flux, i.e., the number of meteors crossing a unit surface on the earth within a unit time, is best fitted by a power-law with a population index of $r = 1.5 \pm 0.3$ within the range $-3 \leq m_V \leq +1 \text{ mag}$. We summarize their data in table 2 and figure 3 together with our flux value ($2.94 \times 10^{-5} \text{ km}^{-2} \text{ s}^{-1}$ at $m_V = 9.70$), derived by taking into account the zenith distance of the radiant points when we observed ($\sim 50^\circ$) and by assuming a meteor altitude of $\sim 115 \text{ km}$ from the sea level (Fujiwara et al. 1998). Though data points in the range $+4 \leq m_V \leq +9 \text{ mag}$ are missing in figure 3, and our flux value may be erroneous because we detected only one meteor, our data point is likely to be in a range that can be predicted by extrapolating the power-law function best fitting the meteor flux at $-3 \leq m_V \leq +1 \text{ mag}$ (Watanabe et al. 2002), indicating that there is no apparent cutoff in the magnitude range brighter than $+10 \text{ mag}$. Furthermore, considering the Poisson distribution for a meteor detection, the confidence interval at the 95% significance level is from 0.24 to 5.57. This range of the meteor number corresponds to a flux range from 7.11×10^{-6} to $1.64 \times 10^{-4} \text{ km}^{-2} \text{ s}^{-1}$.

Finally, we suggest a possibility that the magnitude distribution in figure 3 may consist of two components originating from the two distinct dust trails. In fact, although

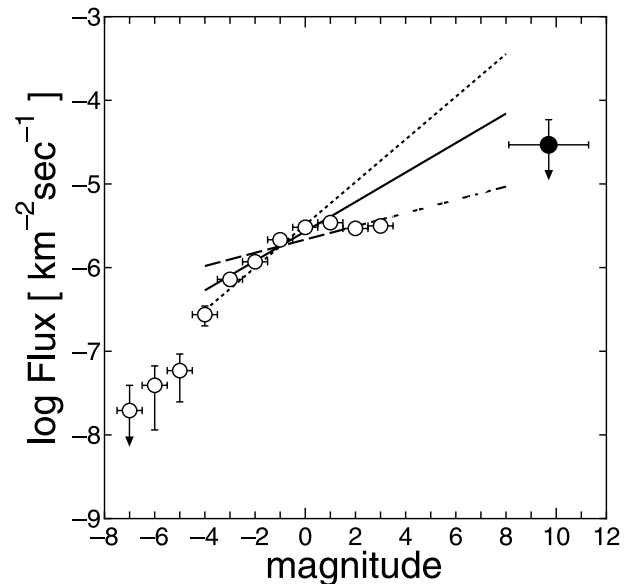


Fig. 3. Magnitude distribution of Leonids 2001. The filled circle indicates the data point obtained in this work. The open circles denote the data quoted from Watanabe et al. (2002), which are best fitted by a power-law with an index of $r = 1.5 \pm 0.3$ over a magnitude range $-3 \leq m_V \leq +1 \text{ mag}$. Three lines, defined by $r = 1.2, 1.5$, and 1.8 , are shown for comparison. The error bars in the flux represent \sqrt{N} counting uncertainties, and the arrows indicate a negative infinity.

there is a turnover in the luminosity function displayed in figure 3 at $\sim 0 \text{ mag}$, the flux starts to increase again at $m_V \simeq +2 \text{ mag}$ along with the magnitude. Data in the range from ~ 4 to $\sim 9 \text{ mag}$ would provide useful information to determine whether Leonids in 2001 really comprises two components or not. This issue, i.e. the magnitude distribution from ~ 4 to $\sim 9 \text{ mag}$, will be clarified in the near future by K. Ohnishi et al. (in preparation) based on the observations toward Leonids in 2001 using the 20 cm telescope at the Akeno Observatory and two 30 cm telescopes for gamma-ray burst follow-up observations at Riken.

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