The radiant of the Leonids meteor storm in 2001

Ken’ichi TORII and Mitsumiro KOHAMA
Cosmic Radiation Laboratory, RIKEN, 2-1, Hirosawa, Wako 351-0198
torii@crab.riken.go.jp
Toshifumi YANAGISAWA
National Aerospace Laboratory of Japan, 7-44-1 Jindaiji Higashi-machi, Chofu 182-8522
tyanagi@nal.go.jp
and
Kouji OHNISHI
Nagano National College of Technology, 716 Tokuma, Nagano 381-8550
ohnishi@ge.nagano-nct.ac.jp
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588

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Abstract

We have measured the radiant of the Leonids meteor storm in November 2001 by using new observational and analysis techniques. The radiant was measured as the intersections of lines which were detected and extrapolated from images obtained at a single observing site (Akeno Observatory, Japan). The images were obtained by two sets of telephoto lenses equipped with cooled CCD cameras. The measured radiant, $(R.A., \, Dec.) = (15^\circ4.35, 21^\circ5.55)$ (J2000), is found to be in reasonable agreement with the theoretical prediction by McNaught and Asher (2001), which verifies their dust trail theory.

Key words: methods: data analysis, meteors, Solar system: general, comets: individual (55P/Tempel-Tuttle)

1. Introduction

Recent progress of numerical celestial mechanics has made it possible to accurately predict the occurrence time, position, and rate of meteoric activities (e.g., McNaught, Asher 1999; Lytton & Flandernet 2000; McNaught, Asher 2001). These theories predict that meteor storms occur when the Earth passes through the dense regions of meteoroids, or dust trails. The dust tubes are produced along the trails of the comet near perihelion passages and are kept in narrow tubes by combined effects of gravitational perturbations from planets and solar radiation pressure. The development of dust trail theories is important not only from celestial mechanics or interplanetary physics points of view but also from planning the strategies for protecting artificial satellites or manned missions against collisions of meteoroids (e.g., Pawlowski, Hebert 2000; Brown, Cooke 2001).

Although these theories have successfully predicted the peak time of meteoric activities, no extensive verifications have been made from other aspects. Since the radiant of meteors is directly related to the dust trails, the observational measurements of the radiant can be critical test for the dust trail theories. For 2001 November activity of Leonids meteor streams, McNaught and Asher (2001) predicted the presence of two strong outbursts ($ZHR \sim 2000$ and $8000$) over East Asian longitudes each of which is due to meteoroids released from the comet 55P/Tempel-Tuttle around its 1699 (9 revolutions ago) and 1866 (4 revolutions ago) return, respectively.

We have thus made observations for verifying the dust trail theories (Ohnishi, et al. 2002; Yanagisawa, et al. 2002). Our method differs from conventional ones in several ways. We use cooled CCD cameras with relatively narrow field of view optics. These instruments enable accurate ($\leq 10$ arcseconds) measurement of each meteor with reference to background fixed stars. We have also employed a new image processing technique (Yanagisawa, et al. 2001) which effectively picks up faint line shapes of meteors superposed on the background fixed stars. Our aim here is not to measure the orbit of each meteor as conventionally studied but to measure the apparent radiant point projected on the celestial sphere. We therefore did not make the observations from multiple observing sites. Two sky positions which subtend nearly right angle to the predicted radiant were observed. Radiant is obtained as the intersections of orthogonal lines detected from the two cameras.

2. Observations

Observations were made on 2001 November 18 UT on the premises of Akeno Observatory ($35^\circ47^\prime$N, $138^\circ30^\prime$E, 900m altitude) of Institute for Cosmic Ray Research, University of Tokyo. We used unfiltered telephoto lenses with the focal lengths of 180mm (Nikkor) and cooled CCD cameras as summarized in table 1. Camera 1 is Apogee’s AP7p with the backside illuminated CCD SITe SI-032AB

\footnote{The technique is patent pending.}
Camera 2 is Apogee’s AP6E with the Kodak’s CCD KAF-1001E (1024×1024 pixels of 24μm×24μm). The exposures were continuously made with integration times of 20-s. Readout times are 10-s and 3-s for the cameras 1 and 2, respectively, which result in ∼33% and ∼13% of dead time in the observation. The pixel scales were 28″/pixel and 27″/pixel for the cameras 1 and 2, respectively. Limiting magnitudes for background fixed stars were ∼12−13 mag for a single frame. These cameras were placed on an equatorial mount and tracked at the sidereal rate. The pointing positions (centers of the field of view), as summarized in table 1, subtended ∼90° to the expected radiant. Camera 1 pointed at a position about −20° (minus sign means westward) away from the radiant along right ascension while the camera 2 pointed at a position about +40° (plus sign means northward) along the declination. The position angles of the cameras were slightly rotated from the north so that the line shapes of the meteors do not become parallel to the column or row of the CCD pixels. This setting reduces the false events due to instrumental effects (e.g., column defects of the chip). Table 2 shows the start times of exposures for the first and last frames for the two cameras as well as the total number of frames. The weather condition was very good and no significant clouds bothered our abbreviations.

We detect linear shapes of meteors from the obtained images and extrapolate the lines toward the radiant. The radiant is thus determined as intersections of many lines detected by the two cameras. Systematic errors for the determination of lines come from several factors. First, the fixed stars revolve 15T cos(δ) arcseconds during the integration time of T [s], which leads to uniform error within ±2.5′ for the current observation (T = 20[s]). In the current configuration, an error in the angle determination of a line corresponding to 1 pixel is magnified to 1.7 and 3.4′ at the radiant. These two factors are combined to make total systematic error of ∼4′. This value is marginally smaller than the expected separation (∼0.7′) of the two radiances corresponding to the dust tubes of 4-revolutions and 9-revolutions ago (McNaught, Asher 2001). Figure 1 shows some bright meteors as observed by the current system. This image was created by stacking 65 frames from camera 2.

3. Analyses

The data were stored in the local hard disk and later processed offline. After dark frame subtraction and flat fielding, astrometric measurement was made for each frame with reference to USNO-A 2.0 catalog (Monet, et al. 1998). The softwares PIXY2 and imwcs 3 were used and the field center and the rotation angle were determined for each frame. The accuracy of the astrometry (field center) is typically better than the pixel scale and that for the position angle is typically better than ∼0.01″.

We have used the new method (Yanagisawa, et al. 2002) for detecting meteors from the observed frames. This technique was originally developed for detecting trails of space debris or artificial satellites from CCD images while it can be generally used for detecting line shapes on two dimensional images in the presence of point-like backgrounds. The details of the algorithm is described in Yanagisawa, et al. 2002 and the method is briefly explained here. Each image is rotated around its center by a trial angle θrot. Then the central square region is extracted and the median values of each row is calculated and stored. In the absence of a line in the image, the median values are randomly distributed as background levels. If a line is present and the rotation correctly puts the line along the row, the median value becomes higher than those of adjacent rows, due to the systematic shift in the distribution of the pixel values toward higher side. Since the presence of point-like stellar images does not systematically shift the distribution, this technique effectively picks up line shapes from the background stars and noise fluctuations. For detecting a line of unknown angle, we make trials with different rotation angles θrot with small steps. In the current analysis, we subtracted the (i−1)-th image (image of the previous exposure) from the i-th image so that the effects of fixed stars and small imperfection of flat fielding are further reduced.

3.0.1. Results

We have examined the appropriate thresholds to discern real events (lines) from background fluctuations. To do this, we have created histograms of rotation angles at which the lines were detected. For bright real events, the angles are concentrated toward the radiant, while the background events are uniformly distributed. We set the thresholds so that the signal to noise ratios are more than

Fig. 1. Sample bright meteors as observed by camera 2.
the threshold distance

the position and the lines. If the number of lines within
centration of the lines in the following way. For each grid
ber of detected line for the camera 1 is partly due to the
observation at the same site.

This procedure has thus three free parameters,
and that positions is considered as the correct radiant.
The extrapolated lines are shown at around the
Fig. 2. The extrapolated lines are shown at around the
predicted radiant. Horizontal (east-west) and vertical
(north-south) lines show those from the camera 1 and 2, re-
respectively. These lines are obtained by extending the origi-
ally detected lines back toward the radiant.

The measured position is also found to be in reasonable

2 in the histogram. Consequently, the limiting magnitude
of the current observation is estimated to $\sim 7$ mag for
meteors by the cross calibration with the wide-field TV
observation at the same site.

As the results of the line detection analyses, we detected
9 and 80 lines from the camera 1 and 2. The small num-
ber of detected line for the camera 1 is partly due to the
presence of a stellar cluster (M 44 = NGC 2632) and a
bright star ($\delta$ Cnc, $\sim 3.9$ mag) within the field of view
which made background higher than that for the camera
2.

Based on the astrometry of fixed stars, we have con-
verted the positions of each line to the celestial coordi-
nates (right ascension and declination) and extrapolated
(extended) back to their origin on the spherical coordi-
nates. The apparent position of radiant moves due to the
combined effects of diurnal aberration and zenithal attrac-
tion. These effects smear out the apparent radiant in a
short time of interval and makes it difficult to resolve the
radiant structures. We therefore calculated the shift as a
function of time and corrected the positions of each line
to cancel the effect. The reference time for this correction
was set to November 18 18:13 UT which was the predicted
peak time for the 4-rev trail encounter (McNaught, Asher
2001). This procedure makes it possible to combine data
of long duration to improve the statistics. The result is
shown in figure 2 and 3. The lines are distributed around
the expected position while we can clearly see the concen-
tration at around ($\alpha$, $\delta$) = (154°.35, 21°.55).

To clearly see the radiant, we have examined the con-
centration of the lines in the following way. For each grid
point near the radiant, we calculated the distance between
the position and the lines. If the number of lines within
the threshold distance $r_{th}$ is more than the threshold num-
bers, that positions is considered as the correct radiant.
This procedure has thus three free parameters, $r_{th}$, $n_1$, and $n_2$ which are not given apriori. We use $r_{th} \leq 4\arcmin$, $n_1 \geq 3$, and $n_2 \geq 15$. This value of $r_{th}$ is chosen so that the value
is comparable to the systematic error as estimated above.
The values of $n_1$ and $n_2$ are determined by the number of
detected lines. Particularly, the value of $n_1$ had to be set
to as small as 3 due to the small number of detected lines
from the camera 1. The value of $n_2/n_1$ may be reason-
able, taking into account the effective area and exposures
of the two cameras. Figure 4 shows the radiant structure
as finally determined.

The position derived in the current work is in reasonable
agreement with the theoretical prediction of McNaught,
Asher 2001. The measured position in declination looks
dispersed by $\sim -0\degree.1$ from that predicted (Figure 4).
However, we may not conclude that they are inconsis-
tent, taking into account the small number of east-west
lines used to constrain the declination. The better con-
strained right ascension is consistent with the prediction
both in the central position and the extension. Although
we expected to resolve the two radiants from the two dust
trails, they could not be resolved partly due to the small
number of the east-west lines and partly due to the rela-
tively large systematic error of the current study. We find
weak evidence of shift of right ascension from RA$\sim 154\degree.4$
to RA$\sim 154\degree.3$ by the time resolved analysis. Although it
is as expected from the peak times of the two dust trails,
limited statistics does not allow us to conclude that they
unambiguously come from the two distinct points or from
relatively extended ($\sim 0\degree.1$) region.

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### Table 1. Observing Instruments.

| Camera | Optics  | Field of view | Center of the Field (J2000) |
|--------|---------|---------------|-----------------------------|
| 1      | 180mm f/2.8 | 3.9°×3.9°     | (08 48 25, +19 21 38)       |
| 2      | 180mm f/2.8 | 7.8°×7.8°     | (09 23 00, +65 06 02)       |

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### Table 2. Observation Log.

| Camera | Start time [UT] | End time [UT] | Exposure [s] | Total number of frames |
|--------|-----------------|---------------|--------------|------------------------|
| 1      | 2001 November 18, 15:11:43 | 2001 November 18, 20:52:31 | 20           | 671                    |
| 2      | 2001 November 18, 16:34:38 | 2001 November 18, 20:21:04 | 20           | 601                    |

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Fig. 2. The extrapolated lines are shown at around the
predicted radiant. Horizontal (east-west) and vertical
(north-south) lines show those from the camera 1 and 2, re-
respectively. These lines are obtained by extending the origi-
ally detected lines back toward the radiant.
Fig. 3. The density of concentration of the extrapolated lines are shown at around the expected radiant. The field of view is the same as that for figure 2. The contour levels show the concentration of 19, 20, and 21 lines.

Fig. 4. The measured radiant structure is shown by filled green dots. The black circle and triangle show the predicted radiant in Tokyo at 2001 November 18 18:13 UT, resulting from the dust ejection at perihelion minus 50 days for the 4-revolution and 9-revolution trails (Adopted from Figure 4 and Table 2 of McNaught, Asher 2001).

4. Conclusions

We have shown that the new method presented here can be a powerful diagnostic tool for studying the radiant structure of meteor storms. The measured position is found to be in reasonable agreement with the prediction of McNaught, Asher 2001 based on their dust trail theory. In 2002, Leonids meteor storm is expected to be observed in North America and in Europe. The observation and analysis method presented herein will be useful to further resolve the profile structure of the dust tubes. Cameras with large area, fast read-out CCDs such as ROTSE (Akerlof, et al. 2000), LOTTIS (Park, et al. 1998), and RAPTOR (Borozdin, et al. 2002, Vestrand, et al. 2002) may be most useful for detecting a large number of meteors in a short time. If enough number of meteors could be detected in a short time, the three dimensional (time resolved) structure of dust tubes may be obtained with the current method.

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