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Evidence for transverse spread in Leonid meteors

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ABSTRACT

We report here evidence for significant transverse spread of the light production region in bright Leonid meteors. One Leonid meteor has an apparent spread in the light production region of about 600 m perpendicular to the flight path for the meteor, that transverse spread persisting for at least 0.3 s. We have also detected short-duration, jet-like features emanating from a bright Leonid meteor recorded in 1998. These jet-like features have maximum spatial dimensions up to 1.9 km. While we cannot definitively rule out instrumental artefacts as a cause for these jet-like features, they may be evidence of motion contributing to the observed spatial spread in the light production region.

Key words: meteors, meteoroids.

1 INTRODUCTION

It is generally assumed (Hawkes & Jones 1975) that meteoroids of cometary origin are a conglomerate of silicate and metallic grains bonded by a material of lower boiling point which may well be predominantly organic in nature. While the proportion of organics relative to silicate/metallic constituents is unknown, and may be very significant (Steel 1998), most of the luminosity of the meteor is produced by atomic excitations following ablation of the silicate and metallic grains and subsequent atomic collisions with atmospheric constituents. For high-velocity meteoroids detected by image-intensified video detectors, the dimensions of the meteoroid ($<3000\,\mu$m) are less than the mean free paths (≈ 1 m) at these heights (≈ 110 km), and therefore one expects the interaction with the atmosphere to be essentially molecular. Conventional thinking is that the size of the luminous region for such meteors is therefore small, of the order of a few metres. While larger meteoroids which penetrate lower in the atmosphere may show fragmentation with significant transverse and longitudinal spread in the fragments owing to a more complex fluid interaction (Brown et al. 1994), this transverse separation is not expected for meteoroids that ablate high in the atmosphere. We would expect that in at least some cases there would be differential aerodynamic drag on grains of different masses, resulting in wake along the line of the meteor flight (Robertson & Hawkes 1992; Shadbolt & Hawkes 1995), but motion of material transverse to the line of flight should be small since no air cap or shock waves are generated. It therefore came as a surprise when we detected significant transverse motions around several bright Leonid meteors observed in 1998.

2 TRANSVERSE SPREAD IN A LEONID METEOR

The meteors reported here were detected using microchannel plate (MCP) second-generation image intensifiers which were lens-coupled to monochrome CCD detectors being run at National Television Standards Committee (NTSC) video rates (30 frames, 60 interlaced video fields, per second). The limiting sensitivities of these detectors are +8 to +9 astronomical magnitudes (depending on lens selection and field of view). The spectral sensitivity of the intensifier photocathode extended from 340 to 870 nm. The meteor images were digitized using a SCION LG-3 card ($640 \times 480 \times 8$ bit monochrome), and analysed using NIH IMAGE v1.61 (no image compression applied to the TIFF images). The meteors reported here were detected from a single location, but we can use the angular velocity of the meteor to establish an approximate range and height for the meteor, after confirmation of shower membership.

At 17:47:12 UT on 1998 November 17 a Leonid meteor with a strongly nebulous appearance was detected by the Mount Allison Light Curve experiment (Murray, Hawkes & Jenniskens 1999) on

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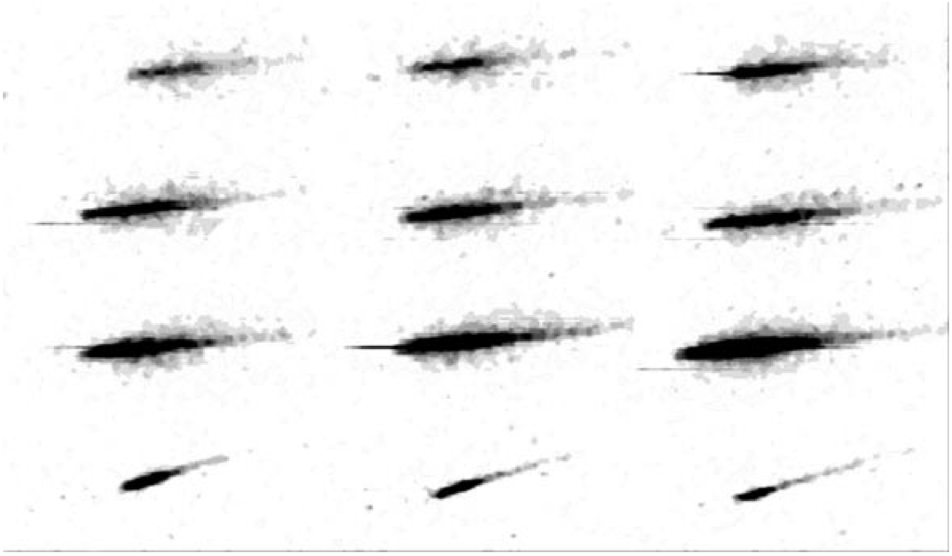

Figure 1. A sequence (with a time interval of 0.033 s between images) for the Leonid meteor which shows transverse spreading observed from the NASA 1998 Leonid MAC campaign. The bottom line of images is a comparison image of another meteor with the same camera. The portion of image shown here is $4^\circ\!.7 \times 2^\circ\!.1$. The image has been corrected for interlaced video scan, and printed in negative mode.

the NASA 1998 Leonid Multi-Instrument Aircraft (MAC) campaign (Jenniskens & Butow 1999). At the time of this detection the aircraft was on a heading of 230° and was flying at a height of 13 km above a point near Okinawa, Japan, at $23^\circ\!.0$ N latitude and $126^\circ\!.5$ E longitude. The camera was oriented at 74° altitude and $356^\circ\!.5$ azimuth at this time. An 85 mm/f2.0 objective lens was used, resulting in a field of view of $9^\circ\!.5 \times 7^\circ\!.3$ and an angular resolution of 0.9 arcmin per pixel. The image sequence for this meteor is shown in the top three rows of Fig. 1. This particular Leonid meteor was clearly nebulous in appearance compared with most meteors. We digitized the segment immediately prior to the meteor and averaged 40 of these video frames to establish a background which was subsequently subtracted from each of the video frames containing the meteor. Also, Adobe Photoshop[1] was used to apply video de-interlacing to the images, and then they were printed in negative mode. The unprocessed images of this meteor have been published by Murray et al. (1999). The horizontal lines in a few of the images are scan line noise, and not real features. In the bottom row we show three images of a 'normal' meteor of corresponding brightness observed with the same camera at about the same time.

The meteor was first observed at a height (relative to the ground) of 138 km and a range (from the aircraft) of 144 km. The meteor had a computed luminosity of about +2.3 mag in the portion of the flight captured, but was still increasing in brightness as it left the screen. The meteor began and ended outside the field of view of the observing system. Another (wider field of view) camera on the NASA Leonid MAC recorded a peak brightness of about −4 mag for this meteor (later in its flight).

We show in Fig. 2 a plot of relative intensity versus distance (expressed in pixels) perpendicular to the line of flight of the meteor. The dotted line is a similar line plot for the comparison meteor of Fig. 1.

It can be seen that, while the comparison meteor has a sharp edge, since its width is dominated by blooming, the nebulous

[1] Adobe Systems Inc., 345 Park Avenue, San Jose, CA 95110-2704, USA.

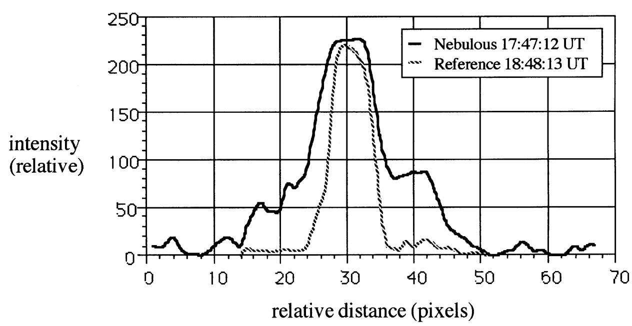

Figure 2. An intensity plot profile, perpendicular to direction of motion, for a Leonid meteor with a nebulous appearance. This meteor was observed at 17:47:12 UT on 1998 November 17 during the Mount Allison University light curve experiment on NASA's 1998 Leonid MAC campaign. For reference, a similar profile for a normal meteor of similar brightness observed on the same night with the same camera is shown by the dotted line. The reference meteor shows only width arising from instrumental blooming, while the nebulous meteor has significant transverse width.

meteor does not have a distinct edge. The apparent width (from centre to edge) of the nebulous Leonid is about 16 pixel, which corresponds to a spatial distance of about 600 m at the range of the oberved meteor. While the detailed appearance of the nebulous meteor changed from frame to frame, it maintained a nebulous appearance throughout the 0.37 s during which it was observed with the higher resolution camera.

A natural question to ask, considering that this was an airborne instrument, is whether the transverse spread is due to vibration in the observing platform. An analysis of the size (owing to blooming) versus magnitude of the stellar images during this meteor, compared with those before and after, indicates that this is not the explanation for the nebulous appearance. A detailed study of the light curves of 65 Leonid meteors observed during this experiment (Murray et al. 1999) indicated no other clear examples of transverse spread.

3 JET-LIKE FEATURES IN A LEONID METEOR

In the early portions of a Leonid meteor recorded from the ground in Mongolia (47°.42 N latitude, 106°.75 E longitude) at 20:02:15 UT on 1998 November 16 we observed the presence of apparent jets emanating from the meteor image. The observing system employed a 25-mm objective lens (which resulted in each pixel corresponding to about 3.15 arcmin), which resulted in a field of view of 33°.2 × 24°.9. This was observed as part of the Leonid 1998 ground-based programme coordinated by CRESTech (Correll et al. 1999).

While several of the bright Leonids demonstrated some hint of jets, the meteor with the clearest example of jet-like features is shown in Fig. 3.

This particular meteor first appeared at a height of 133.2 km at a range of 143.9 km from our camera. The uncertainty in the height is estimated at ±2 km. The zenith angle for the path of this meteor through the atmosphere was 47°. This was one of the longest meteor trails that we observed, with a total trail length of 73 km. Frame 12 (which is the video frame shown in Figs 3 and 4) corresponds to a height of 122 km and a range of 132 km.

We digitized the segment immediately prior to the meteor and averaged 40 of these video frames to establish a background which was subsequently subtracted from each of the video frames containing the meteor. This provides a first-order elimination of artefacts in the intensifier or CCD, or resulting from stars along the meteor path, including those that are not clearly resolved on a single video frame. In addition, the location of faint stars in the averaged background image was checked against the location of the jet-like features. The jet-like features persisted through this image processing.

To remove the artefacts arising from the interlaced nature of the NTSC video, we applied an Adobe Photoshop video de-interlace filter (even field, interpolation settings), followed by a sharpen filter to enhance edges, and manual adjustment of contrast and brightness to accentuate features. The result of this processing on the image of Fig. 3 is shown in Fig. 4.

Six jets are apparent in the processed image (two trailing the meteor approximately in line with the meteor motion, three below the meteor and one above). While the jet-like features are most obvious in this frame, they are apparent in at least four other video frames for this meteor. The length and orientation of the jets vary from frame to frame. We measured the length of each of the visible jets, which ranged from 7.2 to 16.6 pixel, corresponding to 800 to 1900 m. Since the orientation of a jet relative to the line of sight is not known, these distances in metres represent a minimum length. Also, it is not clear where the jet begins on the saturated central part of the meteor image, which adds to the uncertainty in the jet lengths.

This is one of the brightest meteors observed, and an intense flare occurs later in frame 36. This flare so totally saturated the detection system that photometry and deduced photometric masses are very uncertain. Our photometric procedure (Hawkes et al. 1993) suggested that the peak brightness was about −3.5 mag, but the meteor was probably several magnitudes brighter than this. At the time of frame 12 the meteor had a computed brightness of +2.9 mag, although it was near the edge of our field of view in a region of depressed sensitivity.

A natural question to ask is whether the jet-like features are simply some form of interference-related optical artefact. To test for this we used the same camera and recording system to image bright sources while the camera was slewed at various angular rates to simulate meteor motion. The video sequences were digitized using the same equipment and procedures. This test was conducted in 1999 September from a dark sky location under moonless conditions. Other than ambient temperature (which was much colder at about −35°C in Mongolia than the approximately +10°C when the pseudo-meteor images were taken), we believe that we have replicated all observing characteristics of importance. Stars to +0.8 mag, Saturn at +0.8 mag and Jupiter at −2.3 mag were used as sources for these pseudo-meteors. We analysed about 600 video images. None of the stellar images or those of Saturn demonstrated jet-like artefacts, but somewhat similar features were observed on a few of the Jupiter images. A

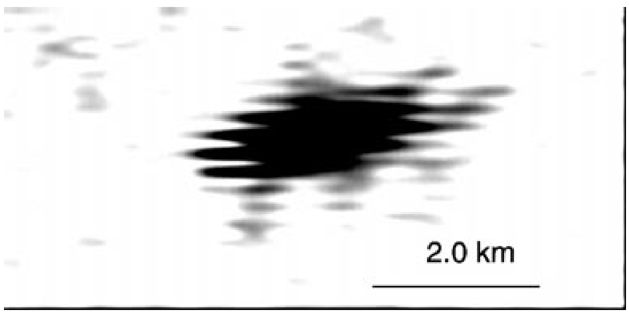

Figure 3. Jet-like features on a bright Leonid meteor. This is the original unprocessed image. The spatial scale shown corresponds to the calculated range of the meteor.

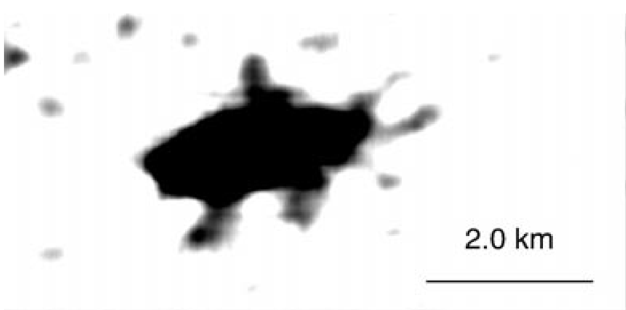

Figure 4. Jet-like features on the bright Leonid meteor of Fig. 3, following video de-interlacing, contrast and brightness adjustment, and sharpen filtering. The spatial scale shown corresponds to the calculated range of the meteor.

Figure 5. Artefacts on a slewed image of Jupiter which bear some similarity to the Leonid meteor jet-like features. The identical set of image processing operations to those performed on Fig. 4 were applied to this image, and the angular scale is the same as in Figs 3 and 4.

closer analysis indicated that these were possibly sequences for which the slewing motion was not completely regular.

We demonstrate in Fig. 5 the image that is most similar to the Leonid meteor jet-like features. The angular scale on this figure is exactly the same as that of Fig. 4, and an identical set of image processing operations (video de-interlace, followed by image intensity and contrast adjustment, and sharpen filtering) were applied. Since the test image was considerably brighter than the meteor image, Jupiter was bloomed to a larger size.

While the appearance of these artefacts is disconcerting, we still believe that the evidence suggests that the features on the Leonid meteor are real. First, they were observed on a much less bright image. Secondly, on the real meteor image there are more jet-like features (six versus two), they are longer, they are not exactly straight (as they are on the pseudo-meteor), they persist over a number of video frames, and they have a variety of orientations, not all directly away from the brightest point, as is the case for the pseudo-meteor. We conclude that the apparent 'jets' in the meteor image are probably a real effect originating with the meteor and not an instrumental effect, although clearly additional observations are required to confirm this observation.

4 DISCUSSION

The features observed here seem confined to the brighter Leonid meteors, and, at least in these examples, occur prior to the point of maximum luminosity. It is not clear whether similar features would occur on fainter meteors, but are lost in the dynamic noise of the observing system, or if the production mechanism requires a large meteor. Similarly, it is not established that these are restricted to Leonid meteors, but rather that we simply have a larger collection of bright fireballs from the 1998 Leonid shower. It is possible that the fact that some bright Leonid meteors begin very high in the atmosphere (Fujiwara et al. 1998) may be important.

The question naturally arises as to why these phenomena have not been previously observed. It may well be the case that photographic observations do not have the temporal resolution to observe the features, and that the dynamic range limitations and noise levels of typical image-intensified video detectors have masked the features. Alternatively, it is possible that these phenomena are only present in showers with meteoroids recently released from the parent comet, and that they are further restricted to bright meteors, and that until the 1998 Leonid shower sufficient data did not exist. It is noteworthy that, even in our sample of 302 Leonid meteors from the ground in Mongolia and 65 from the aircraft, only a few meteors demonstrated these effects.

As this paper was being revised just following the 1999 Leonid shower, a report (Nick Martin, private communication) came to our attention that described visual effects on a few Leonid meteors that were remarkably similar to our jet phenomena. Nick Martin wrote that: 'they [visual features on a few Leonid meteors] appeared to shoot out at an angle of around 30 to 40 degrees from the line of the meteor. They were just like small orangish sparks moving out from near the end of the line of flight of not particularily bright meteors.' A subsequent discussion with Nick Martin indicated that the dimensions of these features were typically 1°, which would be consistent with the features reported here. This report was posted without Nick Martin knowing of the results in this paper, and therefore constitutes independent confirmation of these features.

The transverse spread observed in the nebulous meteor is easier to explain than the jet-like phenomena. This may well be an example of a meteor that has clustered into a number of pieces prior to intensive evaporation [see e.g. the dustball model of Hawkes & Jones (1975), and the light curve models reported by Campbell, Hawkes & Babcock (1999)]. The very interesting brief outburst of Leonid meteors in 1997 reported by Kinoshita, Maruyama & Sagayama (1998) could possibly be an example of a Leonid meteoroid clustered in interplanetary space. The non-Leonid meteor cluster observed by Piers & Hawkes (1993) supports the idea that, at least occasionally, meteoroids fragment in interplanetary space. Separation of Leonid meteors in interplanetary space, with some slight separation of components, possibly owing to radiation forces or rotational bursting (Hawkes & Jones 1978), could readily explain the nebulous appearance. It is interesting that Fisher et al. (2000) have found evidence for transverse separation in the light production region during a search for wake in sporadic meteors.

The jet-like features are a new phenomenon which is also more difficult to explain. It is unfortunate that we do not have better temporal resolution, as it is possible that the time of formation of the jet-like features is even shorter than one video frame time. The raw images appear to show the main jet features in most cases in only a single interlaced video field. However, even if we accept the video frame time (0.033 s) as a duration for the jets, we require extreme velocities of the order of tens of $\mathrm{km\,s^{-1}}$ in some cases, if they are produced by flow of material from the meteoroid. While the two-component meteor ablation model (Hawkes & Jones 1975) is consistent with ejection of a volatile component, it seems unlikely that we can produce the extreme pressure conditions required. Kramer (1968) has argued for relative velocities of the order of those reported here by an explosion and fragmentation hypothesis in some shower meteors. It is possible that the times are larger, but the jet-like features are lost in the dynamic noise level part of the time.

Nevertheless, physical transport of superheated material at the rates required is difficult, and other explanations should be considered. One possibility is that electrostatic forces are important. The meteoroid was perhaps strongly charged, and at some point mutual repulsion became great enough that the object fragmented and the freed grains were then strongly repelled from the remaining object. No significant reaction motion of the main body is noted in the images, however. The recent discovery (Gelinas et al. 1998) of positively charged grains of apparent meteoric origin may lend support to this hypothesis. Bronshten (1991) has considered the charging of a meteoroid as it travels through the ionosphere. Hill & Mendis (1980) provided calculations on the electrostatic potential at which meteoroids of different compositions will fragment.

Sprites are short-duration (the main sprite lasts only a few ms, although there is some luminosity for tens of ms typically) luminous glows generally in the range from 40- to 90-km altitude (Reising, Inan & Bell 1999). In duration, height and physical characteristics they are similar to the jet-like features observed here. Although most sprites are triggered by thunderstorms (e.g. Barrington-Leigh & Inan 1999), recently there has been some suggestion that meteors may also trigger sprite production. Suszcynsky et al. (1999) have reported video and photometric observations of a meteor-triggered jet event in association with the occurrence of a sprite. The jet that they observed, however, was somewhat different from that reported here. The moderately bright sporadic meteor seemed to cause the development of a sprite, followed by a slowly forming jet of luminosity back along the meteor trail. The idea of meteors triggering red sprites was first suggested by Muller (1995).

While we do not consider the evidence of jet-like features absolutely conclusive in light of our slewed pseudo-meteor experiment, we do regard the transverse spread in meteor 17:47:12 UT to be solidly established. This provides evidence that, at least occasionally, shower meteors have significant spread in the light production region.

It is not the role of this paper to do more than briefly speculate on some possible production mechanisms, and we find none of the mechanisms that we have proposed above satisfactory. We hope that others will seek additional observational examples, particularly from high-resolution detectors, and also model possible production mechanisms. While separation of true transverse spread from image effects on the film will be difficult, it is possible that evidence could be found in high-resolution photographic meteor work, although the lack of temporal resolution may well mask jet-like features. Also, the recent development of high-definition image-intensified television detectors (Watanabe et al. 1999) is ideally suited to confirmation of both transverse spread and jet-like features.

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