JET-LIKE STRUCTURES AND WAKE IN Mg I (518 nm) IMAGES OF 1999 LEONID STORM METEORS

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Abstract. Small meteoric fragments are ejected at significant transverse velocities from some (up to ~8%) fast Leonid meteors. We reach this conclusion using low light intensified image measurements obtained during the 1999 Leonid Multi-Instrument Aircraft Campaign. High spatial resolution, narrow band image measurements of the Mg I emission at 518 nm have been used to clearly identify jet-like features in the meteor head that are the same as first observed in white light by LeBlanc *et al.* (1999). We postulate that these unusual structures are caused by tiny meteoroid fragments (containing metallic grains) being rapidly ejected away from the core meteoroid as the constituent glue evaporates. Marked curvature observed in the jet-like filaments suggest that the parent meteoroids are spinning and as the whirling fragments are knocked away by the impinging air molecules, or by grain-grain collisions in the fragment ensemble, they ablate quickly generating an extended area of structured luminosity up to about 1-2 km from the meteoroid center. Fragments with smaller transverse velocity components are thought to be responsible for the associated beading evident in the wake of these unusual Leonid meteors.

Keywords: Fragmentation, jet-like, Leonids 1999, meteoroids, meteors, structures, wake

1. Introduction

Classical meteor ablation theories consider meteoroids to be tiny droplets or single bodies that sometimes include a “fudge factor” to account for fragmentation (e.g., Ceplecha *et al.*, 1998). Fragmentation is an elusive feature of meteor ablation that is responsible for long wakes observed behind some meteors (e.g., Jacchia *et al.*, 1950) that can dominate the shape of the light curves (Hawkes and Jones, 1975; Campbell *et al.*, 1999). Recently, LeBlanc *et al.* (2000) have reported observations of short-lived jet-like features emanating from a single bright meteor imaged during the 1998 Leonid meteor shower. The measurements were made in Mongolia on November 16, 1998 using an unfiltered, intensified CCD imager that had a field of view of ~33° horizontal by 25° vertical and an angular resolution of ~3 arc min. Six jets were apparent in their processed data (five video frames), the length and orientation of which varied from frame to frame. Although several possible explanations for this unusual observation were discussed no firm conclusions could be drawn at that time. In the same paper LeBlanc *et al.,* also present white light images showing a diffuse, nebulous glow associated with one high altitude (~138 km) Leonid meteor imaged during the 1998 Leonid Multi-Instrument Aircraft Campaign. In this case the camera had a smaller field of view of 9.5° by 7.3° (angular resolution 0.9 arc min) and clearly showed a diffuse glow surrounding the meteor and extending out to a range of ~600 m (Murray *et al.*, 1999; Jenniskens and Butow, 1999).

In this paper we present new high resolution (~0.85 arc min) image data recorded during the '99 Leonid Multi-Instrument Aircraft Campaign. The measurements were obtained using a narrow field, intensified imager that was filtered to observe light from neutral magnesium (Mg) emission at 518 nm. The high spatial resolution and narrow bandwidth (~10 nm) of these data were expected to enhance significantly the optical measurements of structure and nebulosity of the meteors during ablation and to help confirm or deny the early reports of jet-like structures.

Initial analysis of the raw images clearly shows well-defined, jet-like features, associated with several of the meteors imaged during the Leonid storm night that evolved systematically from video frame to frame as the meteors ablated. These observations favour one particular explanation, namely the ablation of tiny meteoric fragments. Further signs of fragmentation are the detection of beading in the wake of these (and other) meteors.

2. Instrumentation and Observations

The 1999 Leonid MAC mission consisted of two instrumented B707-type aircraft: the FISTA (Flying Infrared Signature Technologies Aircraft) and the ARIA (Advanced Ranging and Instrumentation Aircraft). Each aircraft was fitted with a diverse array of optical instrumentation designed to investigate the Leonids shower characteristics in exceptional detail (Jenniskens *et al.*, 2000). An extensive mission was flown from the USA to the Middle East (Israel) and back during the period November 13–21, 1999. Both the FISTA and the ARIA flew along parallel paths at an altitude of about 11 km over the Mediterranean Sea from Israel to the Azores during the night of the Leonid shower maximum.

The Utah State University instrumentation consisted of four low light TV cameras (two mounted on each aircraft), designed to study the dynamics of meteor ablation, primarily at two metal atom (magnesium and sodium) emission wavelengths, and to perform a novel investigation of longitudinal variability in the near infra-red (NIR) hydroxyl nightglow emission. The nightglow measurements were made mainly from the FISTA aircraft using two co-aligned imagers: a Gen III Xybion camera and an InGaAs camera (spectral ranges 710-850 nm and 1,100-1,600 nm respectively). However, for this study the primary meteor observations were made from the ARIA aircraft, where two Xybion intensified cameras were mounted together at an ~30° elevation, starboard window, and co-aligned to measure the meteor emission morphology and ablation signatures at selected wavelengths in the visible and NIR spectrum.

Previous spectral studies during the 1998 Leonids shower indicated strong magnesium and sodium emission from meteors as well as from their persistent trains (Borovicka *et al.*, 1999; Abe *et al.*, 2000). Hence, one CCD camera, type RG-350 (756 x 484 pixel array) and equipped with a Gen III image intensifier (spectral range ~350-900 nm), was fitted with a range of filters during the storm night including two narrow band interference filters: one centered on the magnesium emission at ~520 nm and the other on the sodium emission at ~589 nm. Both interference filters had a bandwidth of ~10 nm (full width at half maximum) and a peak transmission of ~50%. This imager was fitted with a 74 mm, f/1.4 lens resulting in a field of view of approximately 8° horizontal by 6° vertical. Video data were recorded onto NTSC standard Hi-8 tapes and the overall system resolution was estimated to be ~560 x 410 lines yielding an angular resolution of 0.85 arc min. This corresponds to a spatial resolution of ~50 meters at the distance of the meteors (~210 km), assuming a mean Leonid height of 105 km altitude.

To aid the interpretation of these data simultaneous “white-light” video observations were also made using a wider field (23° horizontal by 18° vertical) Gen II intensified Xybion camera fitted with a 25 mm, f/1.4 lens. Unfortunately, this system developed an intermittent fault during the mission night and the data are currently only suitable for pointing registration. A time-date signal (accurate to one ms) was also added to each video frame for the narrow field imager to enable easy identification of individual meteor signatures and for detailed comparative studies with other instruments onboard, in particular the Japanese high-definition TV measurements. In due course, it is hoped that these data will provide important additional information on the height distribution of the nebulous, and jet-like meteors discussed here, and to help model their characteristics.

3. Results

Over a hundred meteors were recorded by the narrow field camera at Mg and Na emission wavelengths during the storm night. Estimates of the magnitudes of these events have yet to be made but analysis of white-light imagery from the FISTA aircraft suggest that many of the meteors exhibited peak magnitudes in the range +4 to +5 (Murray *et al.*, 2000). Visual inspection of the raw images has revealed unusual features in several of the meteors recorded in both the Mg and Na filtered data. In particular non-uniformity or "beading" of the light emanating from the meteor trails, and nebulosity with associated transverse “jet-like” features in the meteor head emission appears to be present in up to ~8% of the filtered data. However, further detailed image processing may well increase this estimate.

3.1 STRUCTURE IN METEOR WAKE

Figure 1 shows an example of bead-like structure in the wake of a Leonid meteor imaged in Mg emission at 00:37:15.893 UT. The meteor entered the field of view from the upper-right of the image (~0.4 sec earlier). For clarity the figure shows an enlarged region (~5.6° x 3.4°) of the camera field of view. The meteor trail is well developed and exhibits several persistent luminous “beads” of light separated by depleted regions of luminosity extending along its entire length. Analysis of the video data indicates that these features can endure for several frames. Similar structure in the meteor wake is visually evident in several, but certainly not all, of our filtered meteor image data.

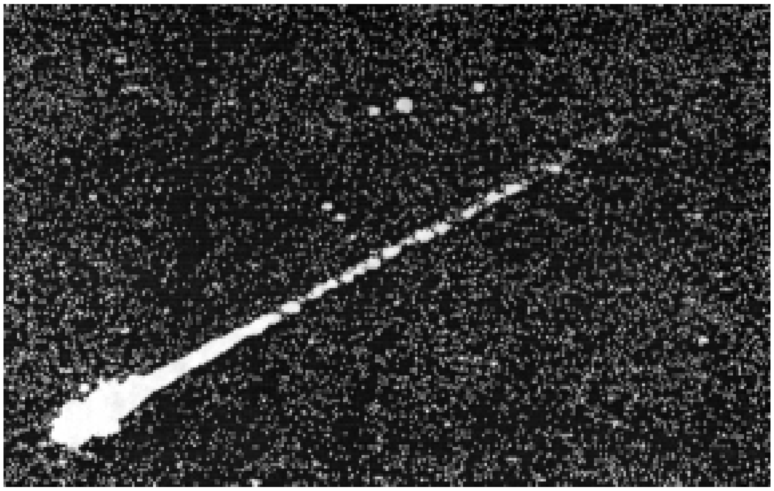

Figure 1. Wake in the path of a Leonid meteor imaged in the MgI emission at 00:37:15 UT showing "beading".

3.2 JET-LIKE FEATURES

Our analysis, to date, has revealed several Leonid meteor events exhibiting "jet-like" features as described by LeBlanc *et al.* (1999). The meteor image of Figure 1 is one such example. This event is shown again in Figure 2 as four consecutive images (each separated by ~33 ms) as the meteor transited across our field of view. The meteor was first detected at 00:37:15.508 UT (as it entered the upper-right of the camera field) and already exhibited a significant transverse spread or glow. This nebulosity was observed to increase in size around the meteor “head” until 00:37:15.659 UT when it reached its maximum extent (~ 1.8 km wide) and jet-like features became evident. The four images of Figure 2 show the evolution of these jets within the luminous region after the meteor had attained maximum brightness.

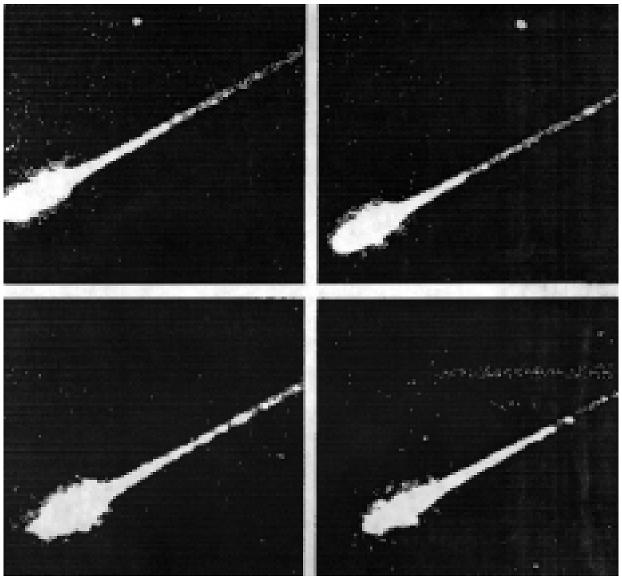

Figure 2. Sequence of images showing meteor "jets" in the Mg I emission at 00:37:15 UT. Note the non-uniformity of the emission and the large jet on the lower side of the meteor image.

About 10 jet-like features can be seen in the Mg emission surrounding the meteor. The jets are not aligned in any one direction and appear to tilt both forward and backwards, as reported by LeBlanc *et al.* (2000). Some jets also appear to have detached from the main transverse spread region and appear as tiny diffuse patches. In particular, one jet (present on the lower side of the meteor images) is most pronounced and extended over several pixels transverse to the meteor motion. This jet was present in several frames suggesting it was a relatively long-lived feature (>0.2 sec) and was still evident as the meteor passed out of our field of view. In comparison, the jets observed by LeBlanc *et al.* were evident only in a single frame of video (i.e. <33 ms in duration).

Figure 3 shows a second example of jet-like features. The meteor was first imaged at 03:08:48.722 UT as it entered the top-right of our camera field. At this time it appeared as a faint dot of light which proceeded to develop into a well-formed nebulous meteor as it grew in luminosity. The two images show a ~50% enlargement of the meteor “head” (265 ms later) as it transited the lower half of our field of view. The top image shows several very well developed jets originating within the luminous region and extending well outside the nebulous area of transverse spread. Unfortunately the image reproduction does not show the details (or contrasts) evident in the raw data. Nevertheless, the jets are prominent and striking in their appearance and over 10 filaments are seen curving both forwards and backwards in an apparently systematic fashion suggesting that the meteor is rotating. The lower figure (33 ms later) shows that the luminous region has decreased significantly in area but the same jet-like features are still prominent. This meteor was somewhat fainter than that of Figure 2 (magnitude not yet estimated), but it still exhibited prominent jets.

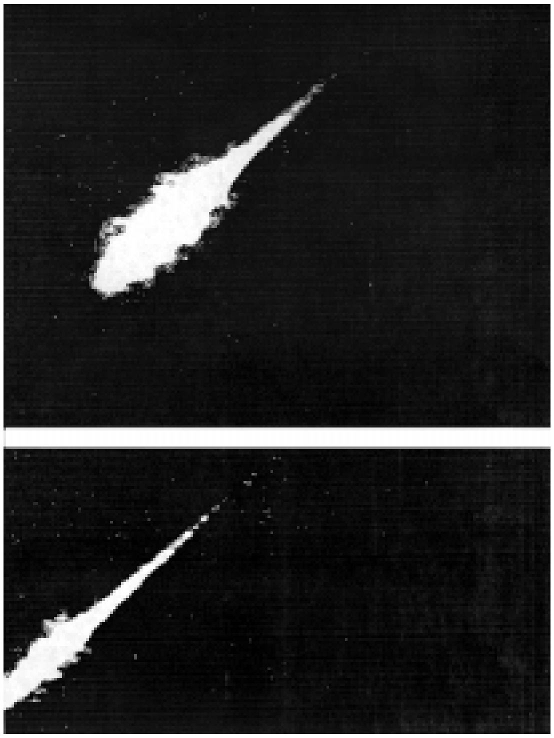

Figure 3. As Figure 2 but for Leonid meteor imaged at 03:08:48 UT. Note, the individual jets are seen to surround the meteor and are initially aligned almost perpendicular to the meteor track but then appear to curve both forwards and backwards suggesting that the meteor is spinning.

Estimates of the scale size of the jets are in good agreement with those determined by LeBlanc *et al*. who found lengths up to ~ 2km. For example, from the tip of the jets to the center of the meteor trajectory, we measure lengths of typically 0.5–1.0 km. This size scale may be relatively independent of meteor size as the jet-like event reported by LeBlanc *et al.* was one of the brightest they recorded during the 1998 Leonids shower, much brighter than the meteors observed here.

One obvious question concerning these measurements is whether the observed jet-like features are real and not simply an artifact of registering a high-speed meteor using an intensified camera system. This question has been addressed by LeBlanc *et al.* (albeit for a different camera system) who found that by rapidly slewing their camera across a bright object, e.g. Saturn (+0.8 magnitude) and Jupiter (–2.3 magnitude), to simulate a meteor signal, they could under certain conditions induce some streaking into the video data. However, they concluded that these features were only evident in the Jupiter data (which is much brighter than the Leonid meteor signals) and that the induced streaks were short and straight and were all directed away from the brightest point. In contrast, the jet-like features reported here and by LeBlanc *et al.* (1999) were more numerous and exhibited clear transverse type structuring at a variety of orientations. Furthermore, our data show marked curvature in some of the jet filaments that appears to be regular indicating that the meteor was probably spinning rapidly. Although we have yet to perform similar tests it is difficult to imagine how such complex structuring could be attributed to an artifact of the camera/recording system alone. Finally, as jets have been found only in a fraction of the Leonid meteors imaged (~8 %) and do not appear to be associated only with bright events there can be little doubt of their authenticity.

4. Discussion

The observed beading in the meteor wake is a strong sign of fragmentation of the meteoroid. Such fragmentation is consistent with the “dustball” model developed by Hawkes and Jones (1975) which pictures the meteoroid as a collection of tiny silicate and metallic grains bonded together by a secondary component of low boiling point “glue”, possibly of organic origin (see also Murray *et al.*, 2000). Smaller fragments released as the glue evaporates are quickly slowed down by the impinging air molecules and will lag the main mass thereby creating the observed beaded trail.

The presence of marked jet-like features in some Mg-filtered images that move with the ablating meteoroid indicates that they are not due to excited atmospheric emissions such as the N_2 first positive band emission (which has a spectral signature within the pass band of the Mg filter). Rather, the data show that it is the ablating material itself that is responsible for these optical structures. A fundamental question concerning the detection of jet-like features associated with the Leonids meteors is that the meteoroids are much smaller than the mean free path (~1 m) at the heights at which the majority of the Leonids ablate in the atmosphere (around 105 km). The interaction between the atmosphere and the meteoroid is therefore expected to be essentially molecular, with no air cap or shock waves generated. Thus, the size of the luminous region should be quite small (a few meters in diameter) (LeBlanc *et al.*, 1999; Boyd, 2000). However, the jet-like structures can clearly surpass this region by a factor of 100.

These data strongly support the concept that the jets may be the signature of plasma effects caused by small fragments containing metallic grains explosively spinning away from the central (rotating) body at speeds as large as 15–30 km/s (perpendicular to the meteor trajectory), as the glue binding them evaporates rapidly. Once the fragments are free from the parent meteoroid, they ablate rapidly in the ambient air causing the whirl-like distributions evident in the filtered emissions. The net effect is deposition of ablated material over a much wider region surrounding the meteor and possibly a higher efficiency of aerothermochemistry than implied by single-body models.

Recent studies indicate that the smallest silicate sub-units in the Leonid meteoroids are about a micron (Rietmeijer and Nuth, 2000) or sub-micron (Greenberg, 2000) in size. However, the fragments responsible for the jets must be significantly larger in order to account for their observed luminosity. Campbell *et al.* (1999) and Murray *et al.* (2000) have considered meteoroid breakup into sub-units to explain the unusual light curve of cometary meteors. Campbell *et al. (1999)* find grain sizes from 10^{-6} to 10^{-12} kg necessary to account for the observed light curves of Leonid and Perseid meteors. In comparison, Murray, *et al.*, have measured light curves for Leonid meteors, similar to the ones studied here, indicating sub-units covering the mass range 5×10^{-13} to 10^{-7} kg (which is equivalent to grain sizes in the range 1–60 microns assuming a mean density of 1 g/cm^3). If the mass-luminosity equation of Jacchia *et* *al.* (1967) applies, i.e. log M (kg) = –4.16 – 0.44 mv, then these sub-units would be expected to produce white light in the range +6.5 to +18.5 magnitude. As mentioned earlier we have not yet estimated the magnitude of the parent meteors. However, the contrast between the jets and the peak intensity of the meteors is clearly large. Assuming a limiting value for the contrast of about 100 (i.e. 5 magnitudes), for a peak white light meteor brightness of +1, the fragment would be about +6 magnitudes which corresponds to ~50 microns in size. This estimate, however, does not take into account the explosive nature of the ablation that appears to be typical for these small fragments. Indeed, their sudden release from the meteoroid in high-densities, often with relative velocities > 72 km/s, may cause significantly higher peak luminosities. Hence, the mass estimate would tend towards an upper limit. This said, these data are consistent with the range of Leonid particle sizes that have been modeled using light curve analysis, and provide independent support for one aspect of the proposed mechanism**.**

In summary, there can be little doubt that the unusual nebulosity and jet-like features that we have imaged during the 1999 Leonids meteor storm are identical in morphology to those recently reported by LeBlanc *et al.* (2000). These new data confirm and extend on their measurements and suggest that this unexpected structuring, which is present in a significant fraction (up to ~8%) of Leonid meteors observed, may in part, be due to explosive ejection of meteoroid fragments possibly in association with rapid rotation. Further, more detailed studies of the jet-like features will be used to provide independent information on the typical grain sizes of meteoroid fragments and the kinetics of fragmentation. It is hoped that these observations will help stimulate new theoretical and modelling studies on the high altitude (typically >100 km) ablation characteristics of fast Leonid meteors.

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