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

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 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.

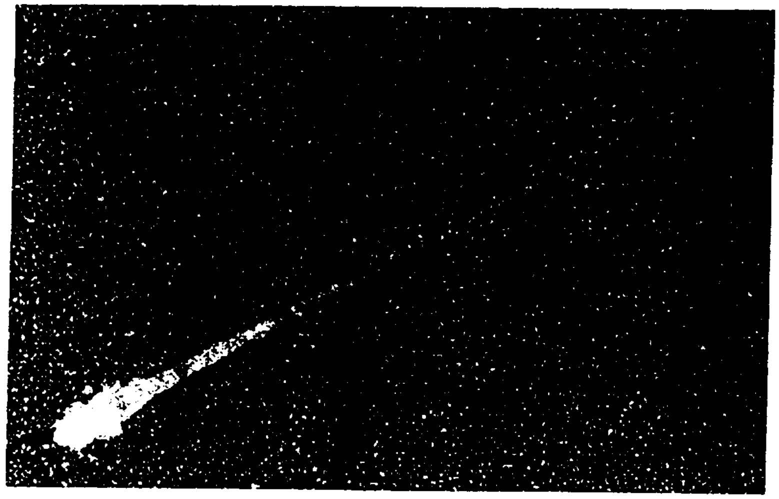

Figure 1. Wake in the path of a Leonid meteor imaged in the MgI emission at 00:37:15 UT showing "beading".

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.

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.

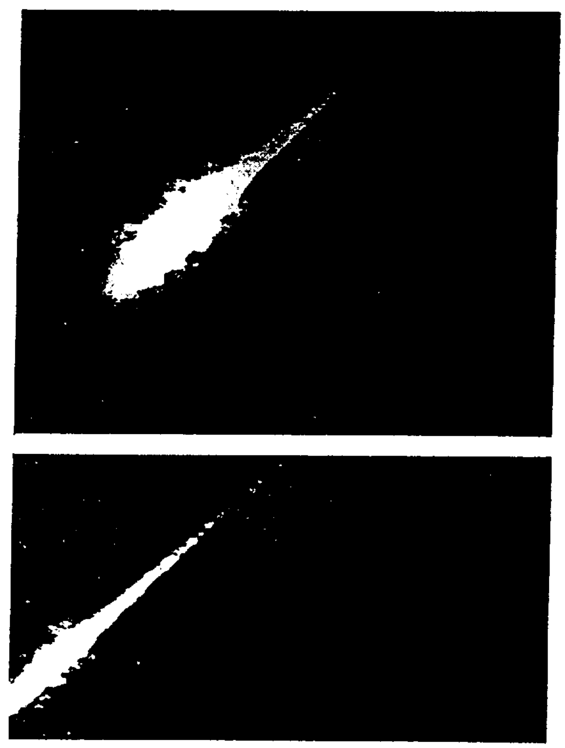

Figure 3. As Figure 2 but for Leonid meteor imaged at 03:08:48 UT. Note, the individual jets are seen to surround the meteor and are initially aligned almost perpendicular to the meteor track but then appear to curve both forwards and backwards suggesting that the meteor is spinning.

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*

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