THE 1999 LEONID MULTI-INSTRUMENT AIRCRAFT CAMPAIGN - AN EARLY REVIEW

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Abstract. The Leonid meteor storm of 1999 was observed from two B707-type research aircraft by a team of 35 scientists of seven nationalities over the Mediterranean Sea on Nov. 18, 1999. The mission was sponsored by various science programs of NASA, and offered the best possible observing conditions, free of clouds and at a prime location for viewing the storm. The 1999 mission followed a similar effort in 1998, improving upon mission strategy and scope. As before, spectroscopic and imaging experiments targeted meteors and persistent trains, but also airglow, aurora, elves and sprites. The research aimed to address outstanding questions in Planetary Science, Astronomy, Astrobiology and upper atmospheric research, including Aeronomie. In addition, near real-time flux measurements contributed to a USAF sponsored program for space weather awareness. An overview of the first results is given, which are discussed in preparation for future missions.

Keywords: Airborne astronomy, astrobiology, chemistry, comets, composition, elves, exobiology, instrumental techniques, Leonid MAC, Leonids 1999, lower thermosphere, meteoroids, meteor storm, meteors, mesosphere, orbital dynamics, satellite impact hazard, sprites

1. Introduction

The widely anticipated return of the Leonid shower in November of 1999 offered our best chance yet to observe a meteor storm with modern techniques. Just prior to the last year's campaign, E.A. Reznikov (in a widely circulated e-mail) predicted from model calculations the return of the Draconid shower on October 8, within 10 minutes of the observed peak. That success raised hopes that the upcoming 1999 Leonid encounter might also be timed accurately. McNaught and Asher (1999) and Lyytinen (1999) used similar methodology and widely circulated an optimistic forecast for 1999 November 18 when the Leonid storm was to

Figure 1. Participating researchers and mission crew.

2. Approach

2.1. MISSION PROFILE

A drawback of last year's approach was the use of two dissimilar aircraft, which included a propeller engine driven Electra aircraft carrying the University of Illinois airborne LIDAR. Because this LIDAR was to be deployed in Antarctica and would not be available for a second mission, we chose to team up the jet engine driven modified NKC 135-E "*Flying Infrared Signatures Technology Aircraft*" (FISTA) with a similar B707-type aircraft, the EC-18 "*Advanced Ranging Instrumentation Aircraft*" (ARIA). The USAF/452nd Flight Test Squadron operates both aircraft from Edwards AFB. This would allow stereoscopic observations along a westward trajectory for a maximum number of night time observing hours. The possible return of last year's fireball shower seen half a day before the nodal passage in 1998 (Arlt and Brown, 1999; Jenniskens and Butow, 1999; Jenniskens and Betlem, 2000), called for at least a three-night mission. Israel was chosen as our prime base, where Dr. Noah Brosch facilitated support of Tel Aviv University and the Israel Space Agency. The USAF/106th Rescue Wing (102nd Resque Squadron) based in New York provided a C-130 ADVON mission, which took care of each other, due to airspace restrictions. The anticipated meteor storm was seen in the next night, Nov. 17/18, under excellent observing conditions while flying just west of Greece on our way from Israel to Lajes Air Base in the Azores (Figure 2b). Two course corrections were made by FISTA to accommodate persistent train observations. During this trajectory the ARIA aircraft was flying south of FISTA. Because the FISTA windows are located on the right side of the aircraft, the overlapping area for stereoscopic work was north of FISTA's trajectory. In that same direction, we observed sprites and elves in an unusual lightning display over Bosnia. During the next night of Nov. 18/19, on our way to Patrick AFB in Florida, the Leonid meteor rates were almost back to pre-storm levels and the tail of the distribution was observed.

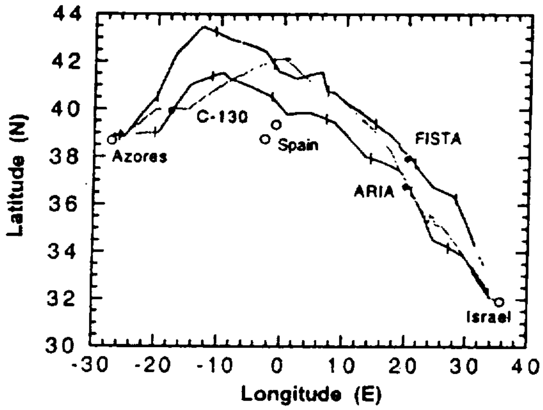

Figure 2b. Detail of Figure 2a for the night of November 18, 1999. Markers indicate 1 hour intervals and the positions of the aircraft at the peak of the storm (02:04 UT) are marked by black dots.

Members of the Dutch Meteor Society set up ground sites for photographic multi-station photography and flux measurements at two locations in Spain (Figure 2b). Czech observers from the Ondrejov Observatory participated in this effort. Sensitive Very Low Frequency (VLF) radio sensors and Very High Frequency (VHF) radar were operated from Israel, aiming for some of the same meteors as seen from the aircraft (Brosch, 2000). ESA established a ground-based effort at measuring meteor flux at the Calar Alto observatory in Spain (Zender *et al.*, 2000), while the USAF sponsored ground-based campaign attempted to view the storm from a site in Israel, at the Canary Islands, and in the Canadian Arctic at Alert, Nunavut (Treu *et al.*, 2000).

head displays and a newly designed counting tool. An intensified CCD camera provided by ESA was included to help calibrate the flux measurements. New experiments on FISTA included the DAISY Fourier transform spectrometer for near-IR spectroscopy of meteors, in a collaboration of NASA ARC with Washington University, while a near-IR InGaAs camera was on loan from the Plasma Physics Division at the Navy Research Laboratory. Two new experiments targeted the 0.3-0.4 micron region for spectroscopy of meteors using Fabry-Perot and grism slit-less spectroscopy. An all-sky camera for meteor imaging on FISTA and small field of view airglow imagers from the University of Utah flew on both aircraft. A new fiber-optic coupled spectrograph was built for meteor trains.

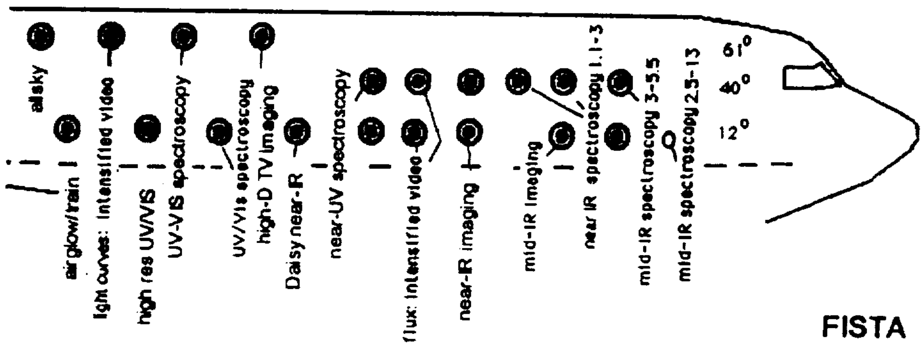

Figure 3. Relative position of instruments on-board FISTA.

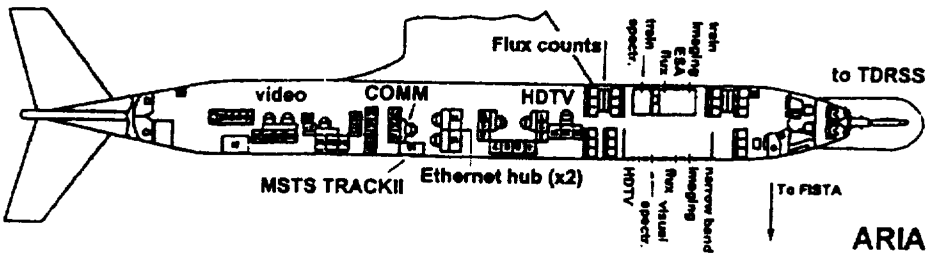

Figure 4. As Figure 3a for ARIA.

Ames Research Center where the compressed digital video signal was simulcast to the Internet. Voice and data communications were also transmitted via MILSTAR and INMARSAT while weather was monitored from the METEOSAT GEO European Weather Satellite System.

The communications can be characterized by three separate modes of operation: Air-to-Air, Air-to-Ground, and Air-to-Space (Table II). Communications between the two aircraft, combined with the first time use of a space-based datalink, facilitated maneuvering coordination and joint tracking of persistent trains. A unique feature of this year was the availability of MS-Track II. The Track II datalink provided continuous 3-dimensional GPS positioning of the mission aircraft. The Track II also supplied e-mail and file sharing capability between aircraft and participating ground stations. This made it possible for the HDTV team to know at all times the direction of the other aircraft during stereoscopic measurements. A VHF voice link (AM2) was used to assist alignment of the fields of view of the HDTV cameras.

A video-editing studio was set up in the back of the ARIA aircraft where the best video image of 8 different cameras was selected for live broadcast to NASA ARC. For that purpose, we used the ARIA 7-foot communication dish mounted in the nose and S-band transmission over the NASA TDRSS network. Flux measurements were transmitted over telephone lines using INMARSAT by means of a local area network on ARIA. The combined capability provided a constant source of real-time data to the Leonid Operations Control (LEOC) at NASA Marshall Space Flight Center (MSFC) and the Leonid MAC command and control center at NASA ARC. Air-to-Ground communications with the Israeli radar site served to correlate real-time surface and airborne Leonid observations during the first two hours on peak night.

A disadvantage of being inside an aircraft as opposed to being in the open air is that bright fireballs and their persistent trains are not easily noticed. To detect fireballs an all-sky camera was connected to automatic meteor recognition software. A warning was to be transmitted over the local area network. Unfortunately, the system was not operational on peak night due to technical difficulties with both the all-sky camera and the mobile frame grabber unit. Fortunately, fireballs and their persistent trains were so numerous that many were detected.

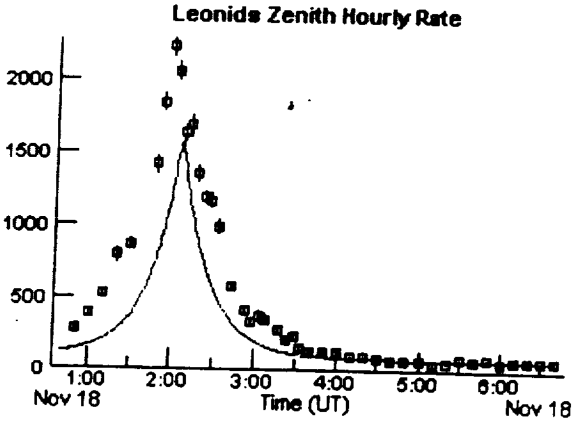

Figure 6. Leonid meteor rates reported in real time by the ARIA flux measurement team compared to the predicted activity (solid line).

The flux rates were compared on-line to predictions built in a JAVA applet called "Leonid MAC Flux Estimator", which allowed anyone on Earth to calculate the apparent Leonid rates as seen from his/her observing site and observing conditions. The applet was posted at the Leonid MAC website in the months leading up to the 1999 storm. The profile contained the expected storm when passing the 1899 ejecta, but also a peak at the predicted time of passing the 1866/1833 ejecta, with assumed peak rates of ZHR = 1,500 for the storm and ZHR = 100 for that second component. The basic ingredients were the predicted peak times (McNaught and Asher, 1999), the width from past Leonid storm profiles (Jenniskens, 1995), and peak rates estimated for past encounters. The comparison was satisfactory (Fig. 6), and demonstrated the advance in recent meteor shower prediction models.

The high meteor rate benefited instruments with a small field of view or low sensitivity. The number of bright fireballs and trains was phenomenal. There were thirteen persistent trains lasting longer than 4 minutes (Table III). During the 7 hours from 23:30 to 06:30 UT, one −13 magn. fireball and one −12 magn. fireball were detected by the ARIA cameras. The afterglow of the former, at 04:00:29 UT, was so bright that it registered on slit-less spectrographs. The persistent train of this meteor was distorted by upper atmospheric winds into a figure "2" and was soon

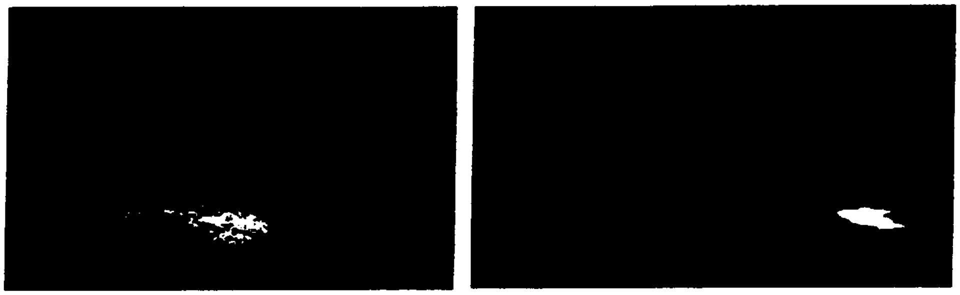

Figure 7. Right: The bright elve of 02:10:00.79 UT in an image from FISTA. Left: Sprites and an elve in a single image from ARIA just above the aircraft engine at 02:48:14.01 UT. Images courtesy Mike Taylor and Larry Gardner, Utah State University.

TABLE IV

Time (UT)	Type	Observer / PI	Instrument
FISTA:			
01:58:11.83[a]	elve	Gardner / Taylor	ICCD1
02:07:35.09[a]	elve	Garnder / Taylor	ICCD1
= 02:07:34.98	elve	Smith / Jenniskens	Daisy
02:08:49.13	elve	Gardner / Taylor	ICCD1
02:10:00.79[a]	elve	Gardner / Taylor	ICCD1
= 02:10:00.72	elve	Smith / Jenniskens	Daisy
02:15:26	sprites	Smith / Jenniskens	Daisy
02:21:28.59[a]	elve	Gardner / Taylor	ICCD1
= 02:21:28.55	elve	Smith / Jenniskens	Daisy
02:23:10.80[a]	elve	Gardner / Taylor	ICCD1
= 02:23:10.65	elve	Smith / Jenniskens	Daisy
02:38:22.12[a]	elve	Gardner / Taylor	ICCD1
02:54:34.34[a]	elve	Gardner / Taylor	ICCD1
02:57:25.59[a]	elve	Gardner / Taylor	ICCD1
02:58:52.46[a]	elve	Gardner / Taylor	ICCD1

a) two-station

The airglow was strong during much of the peak night, in contrast to the exceptionally low levels of airglow detected in 1998. The OH airglow appeared to increase in intensity in relation to the activity of the shower, but other airglow emissions remained unchanged. On the flights to and from Europe, simultaneous measurements were performed from the ground and air in collaboration with the Air Force Research Laboratory (AFRL) at Hanscom AFB (R. Hupti). The ground-based sites were located in New Hampshire (Nov. 13) and in Utah (Nov. 20).

During the meteor storm, a lightning complex over the Balkan was passed at a favorable distance to measure elves and sprites. Eleven sprites and 33 elves were recorded between 1:56 and 3:02 UT. The times are listed in Table IV (FISTA) and Table V (ARIA). Elves are luminous glows in the lower ionosphere, at the altitude of the meteors, due to upward propagation of electromagnetic (ELF/VLF) signals of positive cloud to ground discharges (Figures 7 and 8). The ELF/VLF sensors in Israel recorded some of these. Sprites are upward lightning strokes from the cloud top layer to the altitude of the meteors (the bright light in the right image of Fig. 7, for example).

4. Discussion

These special issues of *Earth, Moon and Planets* (volumes 82 and 83) contain some of the first results presented at the Leonid MAC Workshop that was held in Tel-Aviv, Israel, from April 15-19, 2000 (Rietmeijer, 2000). The first results from last year's mission have been published in special issues of *Meteoritics & Planetary Sciences* (Vol. 34 (6), Nov. 1999) and *Geophysical Research Letters* (Vol. 27 (13), July 2000). So shortly after the observation campaigns, the results are very much a mere "first look" and often raise more questions than answers. However, all tie into a comprehensive study of physical processes that, until now, have remained much ignored.

4.1. SCIENCE ISSUES IN ASTROBIOLOGY

In search for clues to the origin of life on Earth, a key issue is to understand all possible pathways that lead to prebiotic compounds, which include those involving organic molecules in meteoroids, Indeed, Rossano *et al.* (2000) present the first mid-IR detection of meteors from measurements during the 1998 Leonid Multi-Instrument Aircraft Campaign, which show no sign of a persisting wake.

Once released in the Earth's atmosphere, it is important to know the physical conditions in the meteor path and possible chemical pathways involving the interaction with the atmosphere. Borovicka and Jenniskens (2000) calculated the cooling rate of the heated gas from spectra of neutral meteoric metal atom lines in the meteor afterglow of the 04:00:29 UT fireball. Numerous non-thermal mechanisms are observed in this cooling process. Slit-less spectra obtained shortly after a 1998 Leoind fireball were published by Abe *et al.* (2000). Once the afterglow has faded, a long-lasting persistent train remains. During 1999, the first slit-less and slit spectra of persistent trains were obtained at these later evolutionary stages. Apart from sodium line emisison, a yellow continuum is observed that is interpreted as NO_2 (Borovicka and Jenniskens, 2000), suggesting an efficient production of NO, or alternatively is due to FeO emission from airglow-type chemistry (Jenniskens, *et al.* 2000b). The observations appear to confirm the occurrence of airglow-type chemistry but many aspects of the dynamics and appearance of persistent trains are not yet understood (Kelley *et al.*, 2000; Jenniskens *et al.*, 2000c).

A spectacular result was the first measurement of mid-IR emission in persistent trains. Enhanced emissions of CH_4, CO_2 and H_2O were detected, which may originate from trace air compounds or materials created in the wake of the meteor (Russell *et al.*, 2000). Temperatures of $T \sim 300$ K are measured minutes af the meteor, which are consistent with earlier LIDAR probes of the neutral atom temperatures in persistent trains at the Starfire Optical Range by Chu *et al.* (2000a).

Of special interest for understanding the fate of meteoric materials is the detection of a red continuum in the 04:00:29 UT fireball spectrum that is interpreted to be caused by meteoroid debris at $T \sim 1{,}400$ K (Borovicka and Jenniskens, 2000). This temperature is close to the evaporation temperature of silicates at atmospheric pressures in the upper atmosphere (Rietmeijer and Nuth, 2000). Indeed, there is evidence for continuing ablation in part of the afterglow. Given the unusual long lifetimes of neutral iron in the meteor path measured during the 1998 mission (Chu *et al.*, 2000b), this emitting dust is not likely to be re-condensed meteoric vapor but rather debris from fragile cometary grains. Indeed, Rietmeijer and Jenniskens (2000) point out that certain types of spheres reported in the NASA Cosmic Dust Catalogs may be meteoroid

(Jenniskens *et al.*, 2000d). Until now, activity curves of meteor showers were either thought to be Gaussian or exponential distributions. The good statistical precision of the airborne measurements established the shape to be a Lorentzian distribution (Jenniskens *et al.*, 2000d). It is not clear what physical process is responsible for this shape.

The cause of the second Leonid shower peak in the night of Nov. 17, 1998, appeared at odds with the current model, because the Earth passed relatively far from the various trailets. Now, Betlem *et al.* (2000) and De Lignie *et al.* (2000) find evidence that this dust may well have been a manifestation from the 1899 trailet, despite of the recent perturbation of that section of the 1899 trailet by the Earth (McNaught and Asher, 1999; Lyytinen and Van Flandern, 2000).

4.2.2. Meteoroid composition and morphology

In comparing airborne Leonid light curve observations, Murray *et al.* (2000) report a noticeable difference in the shapes of the light curves from the1998 and 1999 missions. In both years, the light curves support the quick breakup of fragile meteoroids but this year's fragments were more abundant in larger pieces.

From narrow filter MgI imaging onboard ARIA, Taylor *et al.* (2000) confirm the occurrence of jet-like features in meteors, seen earlier in white light by LeBlanc *et al.* (2000). This points towards small meteoroid fragments being ejected at high speed.

Preliminary statistical analysis of the meteor time of incidence does not show evidence for breakup of meteoroids upon approach to Earth, which would have produced a significant increase over a Poisson distribution of short time intervals between 1/30 and 1 second (Gural and Jenniskens, 2000). Gural and Jenniskens find evidence of periodic excursions in meteor rates that may be the result of an early breakup of large grains. These excursions may be related to the fine structure in the activity profile reported independently by Singer *et al.* (2000), who find a yet not understood quasi-periodic behavior.

4.3. ISSUES RELATED TO THE SATELLITE IMPACT HAZARD

The '99 Leonid MAC was part of a larger US Air Force sponsored campaign to provide meteor flux data to satellite operators in near-real time (Treu *et al.*, 2000). Leonid MAC provided the most precise flux measurements with meteor rates near the horizon up to 5.3 ± 0.4 times predicted time establishes the overall model of dust trailets (Kondrat'eva and Reznikov, 1985; McNaught and Asher, 1999; Lyytinen, 1999; Lyytinen and Van Flandern, 2000). The discovery of a Lorentz shaped dust distribution in the path of the Earth (Jenniskens *et al.*, 2000d), carries the promise of similar rather a simple analytical distribution of dust perpendicular to Earth's path. If so, the November 2000 return is at the right distance from the 1866 dust trailet for determining the width and position of the trailet in this second dimension. Subsequent encounters of the 1866 trailet in 2001 and 2002 will establish a three-dimensional picture, when we can also measure the decay of dust density away from the comet position.

The discovery of numerous unusually short duration VLF emissions in the 1–20 kHz range at the time of the storm by Price and Blum (2000), has the potential to offer an automatic meteor counting system for future flux monitoring.

4.4. ISSUES IN ATMOSPHERIC SCIENCES

Meteor storms are a natural anomaly of meteoroid influx that can help trace the chemical response of the mesosphere and lower thermosphere. This year's storm provided the detection of enhanced OH airglow that closely followed the meteor storm (Kristl *et al.*, 2000). In addition, Despois *et al.* (2000) report tantalizing changes in the abundance of the upper atmosphere trace compound HCN in the night after the storm, with a promise that many more molecules can be probed in this manner by sub-mm spectroscopy. No changes were found in the sodium airglow (Brosch and Schemmer, 2000). Similarly, (Höffner *et al.*, 2000) show no significant enhancement of the neutral atom potassium layer at the time of the storm.

Persistent trains are natural luminous trails that trace upper atmosphere wind patterns in great detail, notably gravity waves and tides (Grime *et al.*, 2000). Jenniskens and Rairden (2000) find a vertical scale height of 8.3 km at 79–91 km altitude, in good agreement with radar wind data during the 1999 Leonid meteor storm by Singer *et al.* (2000). Further understanding of middle atmospheric chemistry will follow from the spectroscopic, spatial, and temporal analysis of persistent trains, which are now found to have airglow-type chemistry (Jenniskens *et al.*, 2000b). Of interest, too, is the detection of warm atmospheric gasses in persistent trains by mid-IR spectroscopy, which may prove a sensitive

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