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The 2001 Leonid Multi-Instrument Aircraft Campaign — An early review

By

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Abstract: Following a successful deployment in 1999 and predictions of further Leonid storms in 2001 and 2002, a new set of two airborne missions was prepared in the Leonid Multi-Instrument Aircraft Campaign. Geopolitical circumstances affected the scope of the 2001 mission more than usual. The NKC-135 "FISTA" aircraft executed a CONUS single-plane deployment with 19 US citizen researchers onboard out of Edwards AFB, CA. The researchers traveled to Alabama and, after 08:50 UT, slowly returned back to base on a westward trajectory at an altitude of 37,000 ft. Non US citizen participants observed from various ground sites. The 1767-dust trail of comet 55P/Tempel-Tuttle was well observed. Key results were: a) measurements of meteor flux to discriminate among meteor storm prediction models; b) high resolution optical spectra that set a strong lower limit to the CN abundance in meteor plasma and measured plasma temperatures as a function of meteoroid mass; c) further mid-IR detections of meteors with simultaneous optical imaging; d) HDTV recorded low-resolution optical spectra for studies of compositional anomalies in large cometary meteoroids; e) the surprising detection of persistent train emission in a slow and not-so-bright Taurid fireball, as well as f) the observation of an elve at the peak of the storm. Results from ground-based efforts included flux measurements of the 1866 storm peak in Australia, the first high frame-rate images of meteors showing a shock-like feature, and the detection of recombination lines, the UV OH A-X band, and unidentified near-IR emission in meteor persistent emissions. This paper gives a brief overview of the airborne effort and puts the new results in the context of prior work.

1. INTRODUCTION

The 1998 and 1999 missions in the Leonid Multi-Instrument Aircraft Campaign were NASA's firstAstrobiology missions, with the objective to study the interaction of extraterrestrial matter with Earth's atmosphere during a rare meteor storm (Jenniskens and Butow 1999, Jenniskens et al., 2000a). The goal was to learn how comets may have contributed critical amounts or specific prebiotic chemicals necessary for life on Earth and perhaps elsewhere

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in the Solar System. The missions also served to provide impact hazard awareness to satellite operators and were a low-cost mission of exploration to parent comet 55P/Tempel-Tuttle (Beech et al. 1995; 1997, Casswell 1995, McBride & McDonnell 1999). Both missions validated the approach to bring researchers from many disciplines together, to bring them to the best possible location for viewing the event, and to guarantee clear weather and the best possible observing conditions above water vapor. Modern observing techniques helped shed new light on the morphology and the composition of the dust, their dynamics, their particular properties under gas drag, and their impact on Earth's atmosphere (e.g., Ceplecha et al. 1998, Jenniskens 2001a).

Each Leonid MAC mission has been followed by a science workshop, resulting in a liberal exchange of ideas, which has provided direction to later observing and modeling efforts. Contributions were published in special issues of *Meteoritics & Planetary Science* (Nov. 1999) and *Earth, Moon and Planets* (Nov. 2000), which were published before the start of the next Leonid campaign. The latter was reprinted as a 600-page book "Leonid Storm Research". Other results were published in main stream journals. In addition, special Leonid sessions were organized for the AGU, EGS, AIAA, and COSPAR meetings, providing a high visibility platform for the Leonid storm research, and setting the stage for another ambitious observing effort in 2001.

All of this helped turn the 2001 Leonid storm and its science results into the "number 1 cosmic news story in astronomy in 2001" (Astronomy Magazine, *Explore the Universe*, 2003 edition), beating other more traditional astronomical discoveries and news items. Observing conditions were ideal. The Moon was absent and the Leonid storm was spectacular, both over the Americas and Asia. In the USA, millions of people camped outside in the weekend night to watch the Leonid storm unfold much as predicted, restoring a confidence that was lost back when the 1899 Leonids failed to materialize (Hughes 1982).

After the successful prediction of the 1999 Leonid storm, it followed that Earth would cross the 1767-dust and 1866-dust trails of 55P/Tempel-Tuttle in the years 2001 and 2002 (Kondrat'eva & Reznikov 1985, McNaught & Asher 1999, Lyytinen 1999, Lyytinen & Van Flandern 2000). That prediction was supported by the 2000 Leonid observations, when Earth passed near three dust trails (Asher & McNaught 2000, Arlt & Gyssens 2000, Gökel & Jehn 2000, Jenniskens & Gustafson 2000). Some uncertainties remained. McNaught & Asher (1999) predicted that the 1866-dust encounter in Asia and Australia would outshine the 1767-dust trail encounter by a factor of 10, but Jenniskens (2001b) predicted that both 1767 and 1866 dust trail encounter would have similar intensity. Other calculations put the 1799-dust nearest to Earth orbit, predicting a peak over Hawaii, instead (Brown & Cook 2001).

The 2001 Leonid MAC mission was hard to bring together. The World Trade Center attack in September of 2001 introduced new regulations for obtaining flight time authorization which, combined with a late arrival of funding, prevented a two-plane mission and the participation of the AFRL/SRL team and foreign nationals in the 2001 Leonid MAC mission. Moreover, the heavy use of in-flight tanker aircraft such as FISTA shortly after, prevented an extended mission to Guam. Instead, we chose to focus on the 1767-dust trail encounter. Jenniskens (2001b) identified a systematic shift in the calculated trail positions that would put the 1767-dust closer to the Earth's orbit and the 1866-dust trail further away, thus improving chances that the 1767 dust trail would be sufficiently intense to warrant an airborne campaign.

With support of NASA's Astrobiology program, 19 US citizens were able to observe the shower over the continental USA on November 18, 2001 (Figure 1). The mission was executed as part of the Aerospace MOEI program. International participants, amongst which is author PJ, observed from various ground locations in California, Arizona, Utah, Alaska, Hawaii, Australia and Japan. This paper describes the airborne and associated ground-based campaigns and gives a brief early review of scientific results.

Fig. 1: Participating researchers and mission crew.

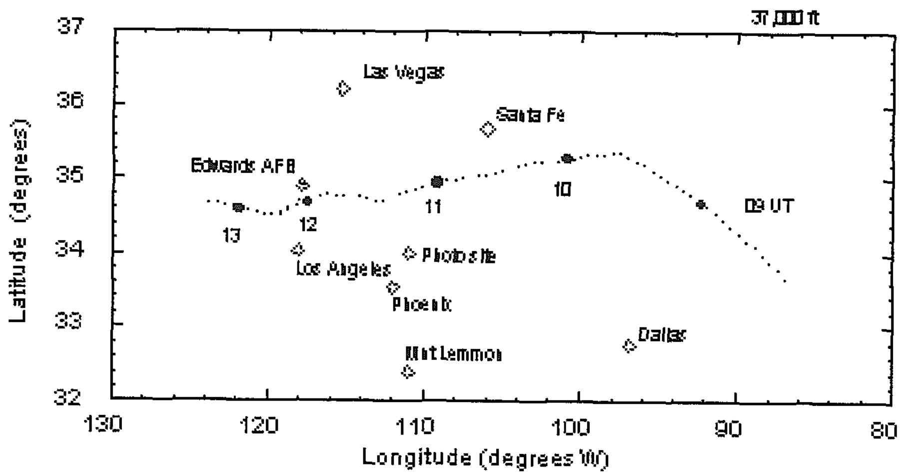

Fig. 2: Flight path of FISTA, after turning point on main mission path. The vertical scale is extended. Times are marked in universal time (UT). The peak of the shower occurred at 10:40 UT.

2. APPROACH

2.1 Mission layout

Of all available aircraft for this purpose, the *USAF/Flying Infrared Signatures Technology Aircraft* (FISTA) offers the most upward looking windows (20 in total). Following an organizational restructuring at Edwards Air Force Base in 2000, the "FISTA" aircraft was now operated

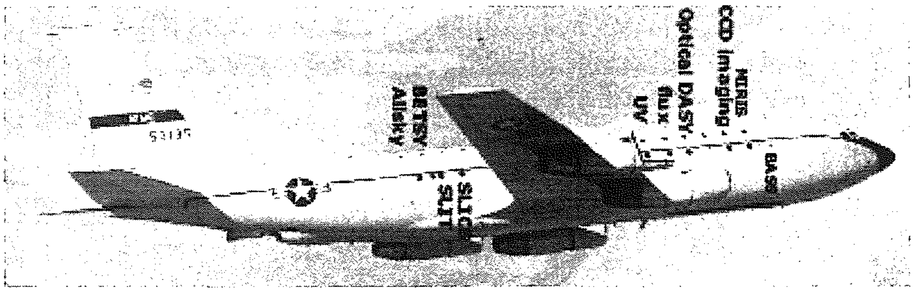

Fig. 3: Instrument layout on FISTA during the 2001 campaign.

Table 1: Instrument parameters.

Instrument	λ (micron)	FOV (°)	$\delta\lambda/\lambda$	Rate (Hz)	Alt. (°)	Target	Affiliation
FISTA:							
BASS	2.5-13	4	30-125	200	12	persistent train	Aerospace Co.
MIRIS	3.0-5.5	15x5	200	16.7	40	meteor/train	Aerospace Co.
White light CCD im.	0.4-0.9	23x18	-.-	30	40	meteors	Aerospace Co.
Daisy optical spectr.	0.4-0.9	20	var.	0.01	40	meteor spectra	Washington U.
White light CCD im.	0.4-0.9	23x18	-.-	30	40	meteors	Washington U.
Fabry-Perrot spectr.	0.52	12x9	90,000	30	30	meteor spectra	Lockheed
High-res UV spectr.	0.30-0.41	37x21	250	30	30	meteor spectra	Lockheed
High-res VIS-NIR	0.4-0.9	5	1,600	0.7	30	meteor spectra	SETI Institute
Low-res VIS spectr.	0.4-0.9	20	120	30	61	meteor spectra	NASA Ames
Slit UV-VIS spectr.	0.3-0.9	1	240	0.5	0-30	train spectra	NASA ARC
All-sky camera	0.4-0.8	180	-.-	30	90	fireballs	SETI Institute
Near-real time flux	0.4-0.8	40,90	-.-	30	22-50	meteor flux	SETI Institute
ground:							
Mid-IR FPA imager	2.5-3.5	4x4	-.-	30	12	meteor	AFRL/Utah State
Low-res VIS spectr.	0.4-0.9	25	200	25	30	meteor spectra	Ondrejov Obs.[2]
Filtered int. video	0.4-0.9	16,10	-.-	30	80	light curves	Univ. Regina[1]
Near-IR InGaAs FPA	0.9-1.67	4x4	-.-	30	20	airglow/meteor	Utah S.U./NRL
Filtered CCD imag.	0.4-0.9	23x18	-.-	30	30	airglow/sprites	Utah State U.
Filtered CCD imag.	0.35-0.8	7x8	52	30	30	trains/meteors	Utah State U.
Intensified HD-TV	0.4-0.8	37x21	-.-	30	0-60	triangulation	ISAS[3]
Intensified HD-TV	0.35-0.9	10-60	250	30	50-90	meteor (spectra)	ISAS[3]
Grism UV-VIS	0.3-0.8	40	200	30	0-60	meteor spectra	NOAO[3]
High Framerate	0.4-0.9	6.4x6.4	-.-	1000	60	meteor imaging	Univ. Alaska
Intensified CCD im.	0.4-0.8	10	-.-	25	15	meteor flux	ESA/SSD[4]

1 Canada; 2 Czech Republic; 3 Japan; 4 Netherlands

by the 418th Flight TestSquadron (formerly called the 452nd). Observations commenced on Nov. 18 at 06:26 UT in a rapid eastward orbit out to Alabama. From a turning point at 08:50 UT, a westward trajectory was followed back to Edwards AFB (Figure 2). Observations continued to a point over the Pacific Ocean until 13:40 UT. Civil twilight started at 14:03 UT. The predicted peak time was 10-10.5 UT, and a mobile multi-station photographic network was setup near the position of the aircraft at that time by the Dutch Meteor Society (Betlem et al. 1999). Clouds forced that effort to be re-located more westward in northern Arizona. Mount Lemmon Observatory acted as the backup ground site for some of our international participants.

2.2 Instruments

While the circumstances prevented the airborne deployment of some new technologies, the team moral was high. The Mid-wave InfraRed Imaging Spectrograph underwent a major upgrade to its light gathering optics and the detector array and electronics. High Definition TV cameras would record the lowresolution spectroscopic data of the BETSY spectrograph (Table I). New experiments deployed on the ground included amongst others the high frame-rate imaging by Hans Stenbaek-Nielsen from a site at Poker Flats, Alaska, and new UV-sensitive intensified HDTV cameras by our Japanese participants.

Special attention was given to the near-real time flux measurements. The successful method developed for the 1999 Leonid meteor storm was perfected (Jenniskens et al. 2000b). Meteors were counted by teams of visual observers that would click on a left mouse button for each Leonid or the right mouse button for a sporadic meteor. The counts were tallied automatically by a flux counting unit developed by Mike Koop and converted into influx data with a new interactive software program developed by Morris Jones. The program enables the comparison of various observers during the observations and corrects the observer perceptions to arrive at the best possible mean. Average flux rates are communicated by e-mail messages once every minute. A ground-based observer, Joshua Kitchener, inserted those numbers in a web-based form and thus updates the database used by graphing algorithms.

The airplane participants would wear video headset displays and count the meteors observed by intensified video cameras positioned at high (50 degrees) and low (22 degrees) angles out of the FISTA windows. Counts were broadcast via INMARSAT to a receiving station at NASA Dryden (Mike Yettaw). The airborne observations were complimented by ground-based observations from Mount Lemmon in Arizona, led by David Holman and Jim Richardson, and from Alice Springs, Australia, in an effort led by Jane Houston and Morris Jones. Both sites were fortunate enough to have clear weather. Graphing tools were developed by Glenn Deardorff and shown at the Leonid MAC website. Interested satellite operator communities also received e-mails. ESOC in Darmstadt published the results for European operators.

3. RESULTS

The intensity of the 1767-dust trail encounter on the night of November 18 UT, 2001, is shown in Figure 4. The peak Zenith Hourly Rate was around ZHR = 1,300 per hour, peaking at around 10:40 UT. The FISTA record was less precise than during the 1999 campaign and counts were reported less frequently, because of a less experienced team of observers onboard the aircraft. Fortunately, the results from Arizona and Australia complimented the data nicely and produced a precise record of near-real time flux measurements, with rates calibrated to within 50%, updated every minute. The intensity of the shower was a factor of three less than expected, the peak was wider and the time of the event was later. All these effects are now thought to be caused by an encounter of Earth with the dust trail in the 1965 encounter (Jenniskens 2003).

The shower was rich in bright fireballs and a long list of bright meteors and persistent trains could be compiled from the video record (Table II). These bright meteors were more dispersed in time than the fainter meteors. One surprise came at 12:54:28 UT on Nov. 18, when a grazing Taurid fireball showed an afterglow during some of its many flares and an unmistaken persistent train (Figure 5). Dean W. Armstrong from Las Vegas photographed the fireball; in a 10-second exposure after aiming the camera at the slow moving fireball. The

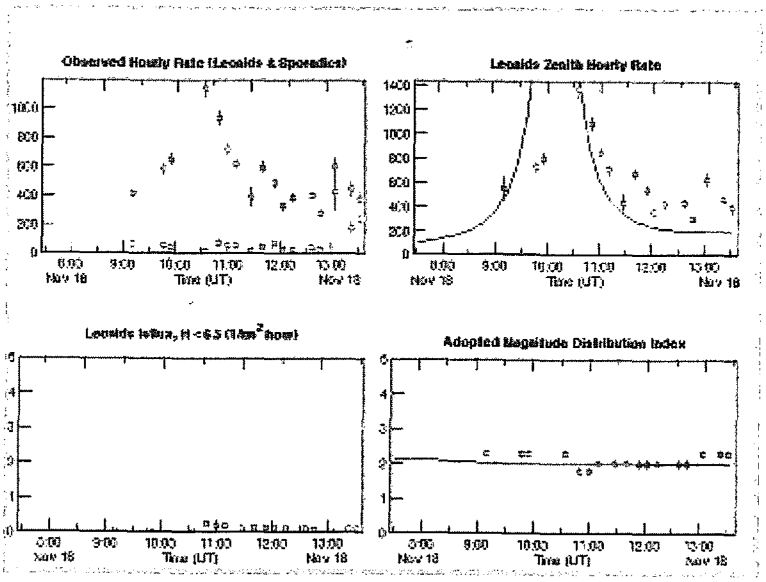

Fig. 4: Near-real time flux measurements from FISTA aircraft.

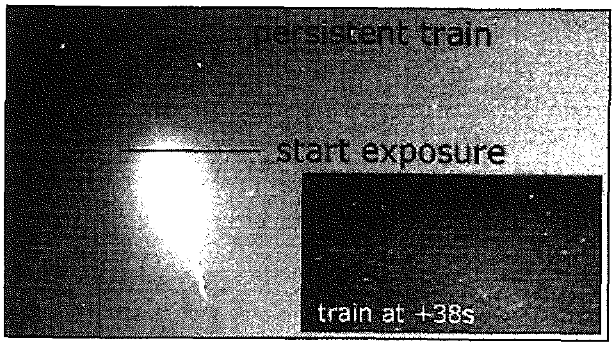

Fig. 5: The 12:54:28 UT Taurid fireball of November 18, 2001, in a ten second exposure by Dean W. Armstrong from Las Vegas, Nevada. The inset shows the persistent train 38s after the event as seen from the FISTA aircraft, from a video record by Mike Koop and Peter Jenniskens.

Dutch Meteor Society cameras in Arizona also recorded the meteor. The photograph shows a persistent emission where the meteor was before the camera was opened. The Leonid MAC video record is spectacular and a persistent train was observed for several minutes, changing shape in the upper atmosphere winds, until the plane changed course. To my knowledge, this is the first time that such train has been reported for such a slow ($\sim$ 31 km/s) meteor. The train is clearly seen early in the trajectory, when the Taurid was only $\sim$ -2 magn., and brightened with time.

Another big surprise came when examining the video data for lightning. Starting at 09:21:19 UT, lightning was observed near the horizon from a lightning complex in Kansas. While the aircraft moved westward, the plane could be seen to gradually travel past this lightning complex. No elves were detected until the final event at 10:29:38 UT, the last lightning flare that could be recorded by the cameras (Figure 6). After that, the plane made a heading correction and the region moved outside the field of view. That elve occurred at the peak of the storm, which

Table 2: This is a table caption.

Time (UT)	Mv Stream (magn. D=100 km)	Duration (min)	From-Until (UT)	h (°)	Az(N) (°)	Camera	Notes
08:55:04	-4 Leo			05	-30	Allsky	Cas
09:02:57	-8 Leo			05	+20	Allsky	Her
09:03:13	-4 Leo	3.5		20		FL50R	Dra
09:03:57	-6 Leo		[09:03:57-09:17]	05	+40	Allsky	UMi
09:15:14	-5 Leo			05	+30	Allsky	Uma
09:19:06	-4 Leo					Allsky	Uma
09:21:15	-5 Leo			30	+20	Allsky	UMa
09:21:19	-8 Leo			20	+30	Allsky	CVn
09:25:19	-.- Leo			-.-	-.-	Allsky	outside fov
09:36:48	-5 Leo	>1	flare			FR50F	
09:42:44	-5 Leo	>1				FR50F	Cep
09:45:37	-4 Leo			05	+00	Allsky	
09:46:03	-4 Leo			30	+10	Allsky	UMi
09:47:38	-4 Leo	1.0		05	-40	FR50F	And
09:47:58	-7 Leo			10	+50	Allsky	CVn
10:02:01	-5 Leo	>3		05	-10	FL50F	Cep
10:07:49	-4 Leo			05	+60	Allsky	Boo
10:15:10	-4 Leo			80	+0	Allsky	Aur
10:15:20	-5 Leo	>2				FL50F	Cep
10:17:37	-5 Leo			10	-60	Allsky	And
10:20:43	-6 Leo			60	+40	Allsky	Dra
10:24:23	-6 Leo	5.0		10	-30	FL50F	Cas
10:26:28	-5 Leo					Allsky	And
10:26:36	-4 Leo	0.5				FL50R	Dra
10:31:51	-4 Leo					Allsky	Cas
10:37:13	-4 Leo	1.0				FL50R	Dra
10:40:50	-5 Leo	1.0				FL50F	Cep
10:43:35	-4 Leo					Allsky	Cas
10:44:32	-5 Leo	3.0				FL50R	Her
10:46:03	-4 Leo					Allsky	UMi
10:50:45	-5 Leo	1.0		05	-10	FL50F	Cep
10:52:32	-7 Leo	12				FL50R	Dra
10:56:13	-6 Leo			60	-40	Allsky	Aur
10:57:52	-6 Leo	>4				FL50R	Dra
10:58:29	-4 Leo	1.0				FL50F	Cas
11:03:15	-10 Leo	>6		05	+40	FL50R	Her
11:04:53	-5 Leo					Allsky	And
11:16:03	-7 Leo					Allsky	Gem
12:21:00[a]	-8 Leo	>17m	[12:24:12-12:41:50]		MIRIS		
12:36:31	-7 Leo					Fl50R	Hyd
12:50:53	-4 Leo			05	-40	Allsky	Per
12:52:48	-8 Tau	> 2m	[12:53:04-12:53:25]	-.-		MIRIS	(12 sec meteor!)
13:20:31	-4 Leo	1.0				FL50R	Dra
13:33:59	-6 Leo	>30s		60	+60	FL50R	Uma
13:35:30	-5 Leo					FL50R	Dra

a) time from scattered light, meteor outside field of view; b) brackets indicate that the persistent train entered or left the field of view; c) flare brings up memories of the 1999 Leonid MAC campaign when elves were observed in unusual abundance from a not-so-unique storm complex over the Balkan (Jenniskens et al. 2000a). At that time, too, the first elves were seen at the peak of the storm.

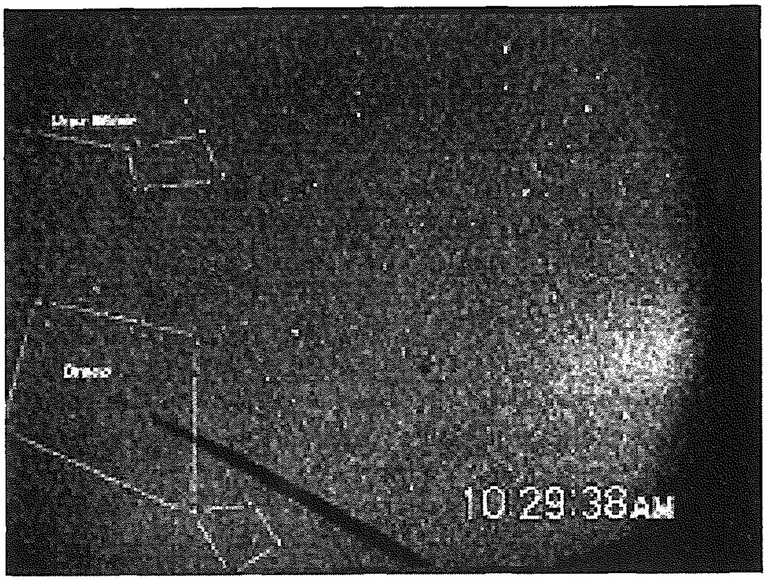

Fig. 6: The 10:29:38 UT elve observed from FISTA from a lightning complex over Kansas. Image by Mike Koop and Peter Jenniskens.

4. DISCUSSION

The first results of the Leonid MAC were presented at the 2002 Leonid MAC Workshop in Tokyo, Japan. This special publication provides a first look of the data. A review is given in the paper by Rietmeijer (2002). Here, we will briefly summarize the results in the context of the main scientific themes of the Leonid MAC, following earlier reviews in Jenniskens & Butow (1999) and Jenniskens et al. (2000).

4.1 Science issues in Astrobiology

Our meteor studies are aimed at understanding the chemical changes in the organic matter carried by the infalling meteoroids (for a review see Jenniskens et al., 2000c, Jenniskens 2001c). Because non-equilibrium chemistry is implied by the rarefied high Mach number flow and short time scales of high excitation collisions, all information that is relevant to characterizing the physical conditions in meteors is relevant. Of particular interest are the experiments that aim to detect organic matter in the meteoroids directly or indirectly, and those that probe the chemical changes to the ambient atmosphere.

The 2001 campaign resulted in the strongest lower limits yet to the presence of CN radicals in the meteor plasma. Jenniskens et al. (2003a) found a lower limit of $[CN]/[Fe] < 0.03$. The lack of CN is tantalizing evidence that the organic matter may survive the warm $T \sim 4{,}400$ K phase in the form of larger organic molecules. However, the nitrogen abundance of the organic matter remains unknown and other fragment compounds such as C_2 and CH should also be searched for. Surprisingly, CN radicals are expected also in aerothermochemistry from CO_2 and N_2 in the ambient atmosphere. A future detection of CN may be able to measure rather the volume of air that is affected by the meteor.

Indirect evidence for the presence of organic matter in meteoroids may come from the presence of hydrogen in the meteor plasma. Hydrogen atoms react rapidly with O_2 molecules to form OH. The 2001 campaign resulted in the discovery of OH emission, from the 310 nm A-X transition in ground-based observations by Abe et al. (2003). Earlier, OH was inferred from photometric measurements in Perseid and alpha-Capricornid emissions (Harvey 1977) and from a tentative detection of OH in spaceborne MSX spectra of a Leonid meteor reported by Jenniskens et al. (2002). OH may also be responsible for excess emission in the near-IR spectrum in Leonid spectra obtained from FISTA, reported by Jenniskens et al. (2003b). The latter represent ground-state transitions and require much lower excitation energy than the hydrogen alpha emission. Ha emission has now been confirmed in Leonid meteor spectra in the special circumstance of an end flare (paper in preparation). One of the CCD spectra shows that the Ha-line has a nearby recombination line of Ca, which in the past may have been mis-identified. Because the atmosphere is very dry at altitude, the most likely source of this hydrogen is the organic matter in the meteoroid. Mineral water or adsorbed water in cometary meteoroids remains a possible source as well. This hydrogen is a potential source of water for the early Earth, perhaps capable of affecting the D/H ratio of ocean water.

Once the organic molecules are released, they are exposed to oxygen atom attack. In order to understand better the chemical evolution to prebiotic compounds, further temperature measurements have been derived from the meteor wake in high frame-rate images (Jenniskens & Stenbaek-Nielsen 2003). The technique of earlier temperature decay measurements from the afterglow of a -13 magnitude fireball by Borovicka and Jenniskens (2000) is now applied to a -3 magnitude Leonid. Again, the plasma is found to cool slower than expected. Meteoroid fragmentation and prolonged survival of debris is implicated. Little is known about the fragmentation properties of very small meteoroids.

Solid debris is a potential source of reduced organic matter. Earlier observations of the 3.4 micron C-H stretch vibration band in meteors (Russell et al. 2000), could not be substantiated with further data. No bright enough persistent train was observed under favorable conditions. At the time of writing, it is not yet known if MIRIS succeeded in capturing a mid-IR spectrum of a meteor. Peterson et al. (2003) captured one Leonid meteor in the mid-IR at $\sim$ 3.5 micron, the first full-length mid-IR record.

The detection of elves in conjunction with the 2001 and 1999 meteor storms calls for further observations during the 2002 encounter. At the time of the origin of life, the meteoroid influx was higher than today by two orders of magnitude, or more, thus creating nighttime conditions not unlike those observed today during a meteor storm. If the meteors can affect the occurrence of lightning, or the way the lightning energy is absorbed in the atmosphere, this can have important implications for atmospheric chemistry on the early Earth.

4.2 Issues related to the satellite impact hazard

Perhaps because of prevention measures put in place and a continuous awareness of meteoroid influx, the 2001 Leonid storms did not result in detected damage to operational satellites. The calculated impact probabilities were only around 1 particle larger than 10^{-5} g for the whole satellite park (Yano et al. 2003) and the storms did not become more intense than expected. Rather than an observational hazard, the Leonid storms were a scientific opportunity to help warn of future more dangerous encounters with comet dust trails.

The meteor stream prediction models have evolved significantly. While the planetary perturbations are relatively well understood, which determine the timing of the showers and identify the storms with past returns of the comet, the dynamics of dust ejection and radiation pressure forces need to be explored further. In the 2001 campaign, two competing approaches predicted very different shower maxima. The simple approach of dust ejection at perihelion taken by McNaught and Asher (1999) and Lyytinen (1999) resulted in two storm maxima at ~10:30 and ~18:00 UT. A competing model by Brown & Cook (2001) was derived from a more complex model of dust ejection over a range of heliocentric distance and a range of ejection speed and direction, as well as a range of particle densities. The result is a combination of dust particles in rather different dynamical orbits and the resulting dust trail positions were significantly different from those above. A peak at 12:00 UT was predicted from dust of the 1799 dust trail.

The 2001 storm observations were able to distinguish between these models and add data to understanding the dust distribution in a comet's dust trail and its precise position relative to Earth's orbit. In particular, the low Australia rates confirm the systematic shift of the dust trails compared to earlier calculations. The absence of a 1799 peak exclude the contribution of particles ejected under certain conditions far from perihelion. The Leonid Filament component rather than the 7-revolution dust trail of 55P/Tempel-Tuttle may be responsible for the broad distribution of bright meteors (Jenniskens & Betlem 2000).

4.3 Science issues in Planetary Astronomy

The Earth's encounter with the dust trail of 55P/Tempel-Tuttle is in many respects a poor-man's comet mission. The dust trail represents the extended dusty atmosphere of the comet at a time when morphology, composition and dynamics still are essentially determined by the dynamics of ejection and the morphology and composition of the dust shortly after release form the comet, but after evaporation of all ice. Ejection velocities can be estimated from the width of the observed dust trail cross section. Of particular interest is the variation of width with meteoroid mass. The precision in meteor counts (N) is proportional to $\sqrt{N}$ which demands high numbers of meteors per time interval for an accurate statistics.

Once the dust trails are identified as such, the progress is mostly in understanding the dust distribution in three dimensions. The new measurements provide fundamental data on the *dynamics of ejection and interplanetary evolution of large sub-mm to cm sized grains that carry* most of the mass loss of comets and represent the comet surface morphology and composition. Jenniskens (2001b) derived a total dust mass loss of the comet in a single revolution of about 2.6×10^{10} kg/return. The width of the showers are a sensitive function of the ejection speed at perihelion, $V_{ej} \sim 9$ m/s. The trail position provides information on the direction of the ejection velocity vector. More complex models of comet ejection are needed to explain some of the unusual features of the shower: the lack of strong size distribution variations across the shower profile and as a function of initial difference in semi-major axis. Jenniskens (2001b) proposed that fragmentation of grains in the comet coma may explain the Lorentz wings of the activity curve.

Jenniskens (2001b) measured a significant shift of the time of peak flux with decreasing magnitude and a gradual widening of the dust trail from 1999 Leonid MAC data. The expected functional dependence between trail width and mass is $W \sim M^{-1/6}$, but can be different if the mass dependence of the ratio of radiation forces to gravitational forces (b) is different than expected or radiation pressure effects such as the seasonal Yarkowski effect are important. Indeed, the observed behavior for the three size groups does not comply. Holman et al. (2000)

discussed the absolute peak dust density in the 1999 storm.

Further analysis of the many light curves (e.g., Murray et al. 2000, Hawkes et al. 2001, Koten & Borovicka 2001) and low-resolution optical spectroscopy (e.g., Borovicka 2001) composition will result in unique data on the possible presence of chondrules/CAI's in cometary matter; on the early breakup of boulders in the comet coma; and on the behavior of large cometary grains under gas drag. The meteor storm offers an opportunity to observe large sub-mm to cm-sized grains for significant content of such nonfine- grained material. The discovery that the meteor plasma temperatures are very constant (Jenniskens et al. 2003c), implies that abundances can be accurately derived. Further insight into the plasma properties are provided by the first (spaceborne) observations of a Leonid spectrum reported in Jenniskens et al. (2002).

4.4 Science issues in the atmospheric sciences

The presence of a persistent train in slow meteors and at a time when the meteor itself was not very bright, suggests that the persistent train phenomenon is related to the cometary (read fragile) nature of the grains, rather than the entry speed or age of the meteoroid. Spectacular images of persistent trains presented at the Leonid MAC Workshop and obtained by Japanese amateur observers will help understand the physical causes of persistent trains, while the detection of unidentified near-IR emission in meteor persistent trains (Borovicka 2003) may help understand the chemiluminescence mechanisms responsible for persistent luminosity (Kruschwitz et al. 2001). Of particular interest, too, is the discovery of recombination line emission as a new phase in meteor persistent emissions (Borovicka 2003).

Prior Leonid MAC missions produced lots of tantalizing indications of phenomena of airglow that needed to be observed again. The 1999 Leonid MAC mission observed an increase in both the OH Meinel emission (Kristl et al. 2000). The implication is that the meteor storm affects airglow chemistry at an altitude ten km lower than where most of the meteoric matter is ablated, which is difficult to explain. Interestingly, no associated increases of Na and the singlet-delta transition of O_2 were observed.

The 2001 Leonid MAC mission did not enable the deployment of the ASUR submm spectrometer to measure the rotational spectrum of upper atmosphere trace molecules. Initial ground-based results on HCN by Despois et al. (2000) were followed up by Nakamura et al. (2003) in search of HCO, but without detection. The high-altitude molecules are recognized as a narrow Doppler broadened feature on top of a broad pressure broadened signal from lower atmospheric compounds. Changes in HCN and other trace gas abundance in the mesosphere (e.g. O_3, HCl, NO, H_2CO) correlated to simultaneous detection of optical airglow emissions of OH, O_2, Na and OI that trace gravity waves, will allow to validate the observed variation of OH. To understand these changes is to understand the role of meteoric influx on upper atmosphere chemistry and, by example, their effect on the atmosphere of other planets.

Preparations are underway for a final 2002 Leonid MAC mission, which will enable the deployment of ASUR, the high frame-rate imager, and other modern techniques.

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