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The 1998 Leonid multi-instrument aircraft campaign—an early review

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Abstract–The 1998 return of the Leonid shower was the target of the Leonid multi-instrument aircraft campaign (Leonid MAC), an unusual two-aircraft astronomical research mission executed near Okinawa, Japan. The prospect of a meteor storm brought 28 researchers of 7 nationalities together in a concerted effort to observe the shower by imaging, spectroscopic, and ranging techniques. This paper is a review of the major science issues that are behind the deployment of each of the present array of instruments and describes the interconnection of the various experiments. This was NASA's first astrobiology mission. The mission also aimed to study contemporary issues in planetary astronomy, in atmospheric sciences, and concerning the satellite impact hazard. First results of the participating observers are discussed and put in context, in preparation for the deployment of a planned second mission in November of 1999.

INTRODUCTION

The famous Leonid meteor storms have played a defining role in recognizing the cause of meteor showers as the high-speed entry into Earth's atmosphere by swarms of meteoroids ejected from comets. The storms of 1799 and 1833 drew the attention of western scientists to meteor showers for the first time (Lovell, 1954; Hughes, 1982). Soon after, it was found that Leonid storms returned with a period of ~33 years and were reported as far back as 902 A.D. The anticipated storm of 1866, and the discovery of parent comet 55P/Tempel–Tuttle in 1865 (shortly after the Perseid and Lyrid comets), provided the direct link between the orbit of a comet and that of a meteoroid stream (Le Verrier, 1867; Schiaparelli, 1867).

The return of 55P/Tempel–Tuttle has created a periodic surge of interest in meteor showers ever since. Initially, that interest was not rewarded. No meteor storm was reported in 1899, nor in 1933. A better understanding of the dynamics behind meteor storms emerged only in modern times. Following Fred Whipple's correct 1950 description of meteoroid ejection from a comet nucleus by the drag of water vapor (Whipple, 1951), it was realized that differences in orbital period, due to ejection velocities and radiation forces, cause these particles to disperse rapidly along the comet orbit after each next return (Plavec, 1955; Kresak, 1976). The resulting dust trails were first observed as such in 1983, when the *Infrared Astronomical Satellite* (*IRAS*) imaged the thermal emission from large dust grains in the orbit of several short-period comets (Davies *et al.*, 1984; Sykes *et al.*, 1986; Sykes and Walker, 1992). Shortly after, it was realized that the time it takes Earth to cross such dust trails is just as long as the duration of a typical meteor storm (Kresak, 1993; Jenniskens, 1995).

The prediction of meteor storms needs massive computing power and is still in its infancy. Back in 1966, a mere beginning was made in addressing the effects of planetary perturbations on the path of comets and their meteoroid streams near Earth's orbit (Kazimircak-Polonskaja *et al.*, 1968). The predicted time of a possible storm was uncertain, and the absence of meteor storms in 1899 and 1933 had lowered expectations. When an intense storm did occur in 1966, seen from locations in the western United States in the late night of November 17, professional observing efforts were low key and many failed due to bad November weather (McIntosh and Millman, 1970). Fortunately, a few key sightings of the parent comet in 1965, together with a rapid development of computing techniques, made it possible to study the comet orbit dynamics and use historic Leonid accounts to map out the dense debris in the vicinity of the comet. The dust was found mainly behind the comet and just outside of the comet orbit (Sekanina, 1975; Yeomans, 1981).

It was clear that Earth would cross that debris trail again during the return of 1998, but not in the next two returns in 2031 and 2065. This would be our one chance in a lifetime to witness a meteor storm. In preparation of the expected event, the orbital dynamics of the comet was revisited (Yeomans *et al.*, 1996), the meteoroid orbits were studied (Lindblad *et al.*, 1993; Shiba *et al.*, 1998; Betlem *et al.*, 1997), past observations of usual and unusual Leonid shower activity were reanalyzed (*e.g.*, Jenniskens, 1995, 1996; Brown *et al.*, 1997), and results of various numerical models were published (Wu and Williams, 1996; Brown and Jones, 1996; Matney, 1996; Williams, 1997).

Parent comet 55P/Tempel–Tuttle returned to perihelion on 1998 February 28, as predicted. The comet reached a visual magnitude of +7.7, which allowed some studies of comet rotation and gas ejection. This was a fairly small comet with a diameter of 3.6 km (Hainaut *et al.*, 1998) and with a rotational period of 15.33 ± 0.02 h (Jorda *et al.*, 1998). The cometary dust was studied by infrared (IR) spectroscopy and did not show the expected 10 μm Si–O stretch vibration band, which suggests that relatively large (>30 μm) grains were being ejected (Lynch *et al.*, 1998).

The first signs of increased activity of the Leonid shower since the previous return in 1966 was reported in 1994 (Jenniskens, 1996). This and subsequent returns were rich in bright fireballs and long lasting trains (Brown *et al.*, 1997, 1998; Langbroek 1999). A series of dedicated observing campaigns were organized with support of NASA's Planetary Astronomy Program for studies of meteoroid stream dynamics, meteoroid structure, and the interaction of meteors with the atmosphere (*e.g.*, Jenniskens *et al.*, 1997, 1998; Betlem *et al.*, 1997). These efforts included stereoscopic measurements for trajectories and orbits, flux measurements, and efforts to aim the telescopes of the European Southern Observatory at long-lasting persistent trains. Clouds often hampered the observations and it became clear that it was important to be at the right place at the right time. With each new outburst, the confidence of anticipating time and place gradually increased.

Observing efforts in the U.S.A. in the years leading up to the 1998 Leonid return were mostly low key. We realized that the 1998 and 1999 Leonid showers would be best studied if an effort was made to bring scientists together, mobilize unusual observing techniques, and bring man and machine as a team to eastern Asia in November of 1998. In order to do so, we had to guarantee clear weather.

The idea to use aircraft to beat the clouds turned out not to be new. The Czech astronomer Vladimir Guth made an effort in 1933 to view the Leonids from a small three-engine Fokker FVII aircraft (Guth, 1934). Stuart Clifton of Marshall Space flight Center pioneered video meteor observations during his participation in the 1969 NASA Airborne Auroral Expedition, aboard the Convair 990 aircraft NASA 711 (Clifton, 1971, 1973). And the Canadian meteor astronomer Peter Millman used NASA's Learjet aircraft in a successful effort to observe the Quadrantid shower with a meteor video spectrograph in January of 1976 (Millman, 1976).

However, a multi-instrument aircraft campaign (hence "Leonid MAC") has several participating instrument principal investigators. A MAC is a common approach in the atmospheric sciences, earth sciences, and aerospace applications; but a MAC targeted at a meteor shower was the first such effort in astronomy.

This paper is an attempt to review how the experiments worked together to attack contemporary science issues. A first tally of results was made during the 1999 April Leonid MAC workshop at NASA Ames Research Center. The current issue and later issues of *Meteoritics & Planetary Science* contain some of the papers presented at this workshop. This paper intends to put those results in context and provide an evaluation of the mission in preparation for the next airborne campaign in 1999 November.

APPROACH

The NASA-sponsored 1998 Leonid MAC was executed with the U.S. Air Force owned Flying Infrared Signature Technology Aircraft (*FISTA*) and the *Electra* aircraft owned by the National Science Foundataion. The use of two airborne platforms enabled stereoscopic observations and accommodated a diverse array of instruments.

The modified NKC 135-E *FISTA* was operated by the 452nd Flight Test Squadron at Edwards Air Force Base, California. The aircraft was ideally suited for the mission because it provided some 20 upward-looking 12" ports, which for the purpose of the mission were refurbished with optical quality glass, and one 6" port for direct thermal infrared spectroscopy. The *FISTA* sensor program of the Air Force Research Laboratory Background Characterization Branch at the Hanscom Air Force Base, Massachusetts, loaned windows, tracking eyeballs, generators, mounts, *etc*., and provided support with sensor installation on the aircraft. Air Force Research Laboratory's Michelson interferometers and the Aerospace Corporation's mid-IR spectrometers were the most elaborate experiments on *FISTA*.

The L188-C *Electra* is operated by the National Center for Atmospheric Research research aviation facility at Broomfield, Colorado. The aircraft is routinely used for atmospheric science. An ongoing National Science Foundation program at the University of Illinois, a two-frequency Boltzmann lidar (light detection and ranging) for temperature measurements of neutral atom debris in the atmosphere, was the core of the *Electra* deployment. The lidar was being installed in the aircraft in the months leading up to the campaign. Experience from prior airborne campaigns (Gardner, 1991, 1995) made it possible to field an all-sky airglow imager of the same institute under an optical glass dome (Swenson and Mende, 1994).

Both aircraft provided a platform for a range of experiments. Six different experiments were accommodated on *Electra* and fourteen on *FISTA* (Table 1). Twenty-eight scientists and support staff of seven nationalities participated in the mission, which was supported by another eighteen crew members. Researchers were from universities as well as from government and private institutes.

TABLE 1. Instruments deployed in the 1998 Leonid MAC.

	Instrument	Wavelength (μm)	Field of view (degrees)	Resolution $\lambda/\Delta\lambda$ (Hz)	Rate	Elevation	Target	Instrument PI	Affiliation
FISTA									
1	CCD imager	0.4–0.8	20	–	0.01	20–60	glow	R. Nakamura	Kobe University
3	Intensified video 2 × 50 + 20 mm	0.4–0.8	40,90	–	30	3–31	meteor flux	P. Jenniskens	SETI
3	Intensified video 2 × 50 + 20 mm	0.4–0.8	40,90	–	30	22–50	meteor flux	P. Jenniskens	SETI
3	Intensified video 300 mm camera	0.4–0.8	5	–	30	61	faint meteor flux	P. Jenniskens	SETI
4	Intensified video 50 + 85 mm	0.4–0.9	16,10	–	30	80	light curves	I. Murray	Mnt. Allison Univ.
5	Intensified HD-TV Imager	0.4–0.8	10–60	–	30	0–60	meteor	H. Yano	ISAS
7	Low-res UV-VIS spectrometer	0.4–0.9	20	120	30	61	meteor spectra	P. Jenniskens	SETI
8	Low-res UV-VIS spectrometer	0.4–0.9	25	200	25	0–40	meteor spectra	J. Borovicka	Ondrejov Obs.
9	Mid-IR Imager FPA	2.5–3.5	4 × 4	–	30	12	meteor	J. Kristl	AFRL/SRL
10	Mid-IR spectrometer MIRIS	3–5.5	15 × 5	200	16.7	40	meteor	G. Rossano	Aerospace Corp.
12	Near-IR spectrometer Bomen	1–1.6	1.5	4000	0.3	20–60	train	J. Kristl	AFRL/SRL
13	Near-IR spectrometer Bomen	1.5–3	1.5	2000	0.91	20–60	train	J. Kristl	AFRL/SRL
14	Mid-IR spectrometer BASS	3–13.5	4	30–125	200	12	train	R. Russell	Aerospace Corp.
14a	SWUIS (BASS support)	0.4–0.9	20	–	30	12	meteor	A. Stern	SWRI
Electra									
2	Airglow imager	0.5–0.8	90	–	0.02	90	airglow	G. Swenson	Univ. of Illinois
3	Intensified video 2 × 50 mm battery	0.4–0.8	40	–	30	22–50	meteor flux	P. Jenniskens	SETI
5	Intensified HD-TV imager	0.4–0.8	10–60	–	30	0–60	meteor	H. Yano	ISAS
6	Low-res UV-VIS spectrometer	0.4–0.9	5	1600	0.7	37	meteor spectra	P. Jenniskens	SETI
11	11" telescope/slit UV-VIS spectr.	0.3–0.9	1	240	0.5	0–30	trains	J. Plane	Univ. of East Anglia
15	Two-beam Fe Boltzmann lidar	0.72, 0.74	–	–	0.1	90	Fe debris trails	C.Gardner	Univ. of Illinois

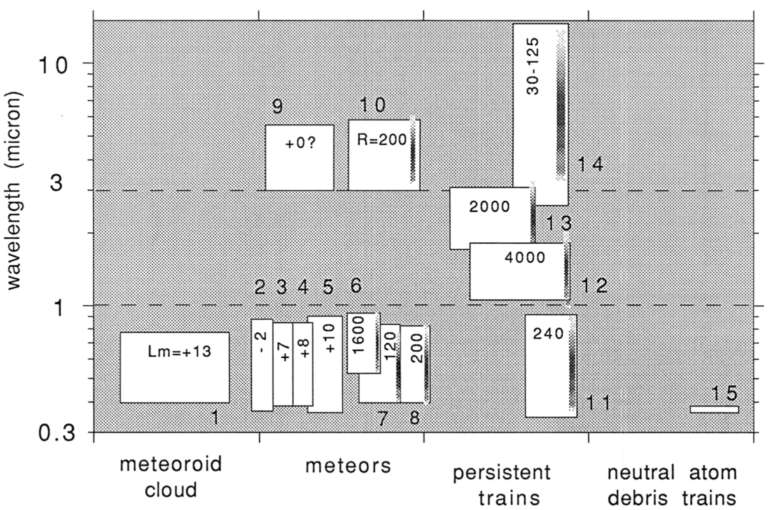

FIG. 1. Instrumental coverage of topical space (*x*-axis), accessible wavelength range (*y*-axis), technique (imager/spectrograph), star limiting magnitude (*Lm*), and resolution (*R*). Numbers outside the boxes refer to the instruments listed in Table 1.

The aim was to minimize costs by using off-the-shelf equipment in mission-ready aircraft. The SETI Institute's principal investigator at NASA/Ames Research Center developed the necessary imaging cameras to provide a documentation of the shower for support of other experiments. Most other instruments were developed for other research programs and underwent only minor modifications, or none at all. The University of Illinois' lidar and Aerospace Corporation's Mid-IR imaging spectrometer (MIRIS) saw their first deployment in Leonid MAC.

The various experiments were directed at four observing targets (Fig. 1): the Leonid meteors were observed by staring cameras, the long-lasting persistent trains were observed by trainable cameras, the neutral atom debris trails were observed by lidar, and the faint glow expected from scattered sunlight in the line of sight towards the incoming Leonid meteoroids was observed by an integrating charge-coupled device (CCD) camera.

The imaging and spectroscopy of meteors covered a wide wavelength range from 0.4 to 13 μm but was not exhaustive (Fig. 1) in terms of the potential range of resolution ($R = \lambda/\Delta\lambda$) and star limiting magnitude (*Lm*). The dynamic range of intensified camera systems and the rapid decline of meteor frequency with brightness puts constraints on the range of meteor brightness that can be effectively covered in each staring experiment of given sensitivity. Also, many techniques were exploratory. For example, no information was available on the near- and mid-IR spectra of meteors, nor was it known how bright a meteor would be required to cause a detectable lidar signal.

The instrument layout on *Electra* is shown in Fig. 2. The two-beam lidar onboard *Electra* measured Fe debris trails (Kane and Gardner, 1993) and probed the potential Rayleigh scattering of meteoric debris (Kelley *et al.*, 1998). The lidar would be deployed at the location with highest meteor fluxes, operate above most tropospheric scattering, and probe debris trails while in motion. Any detections were to be correlated with optical imaging from high-definition television observations of the region near the lidar beam, a technology provided by the Japanese Broadcasting Company (NHK). The camera was mounted in the roof of the aircraft in order to be coaligned with the lidar (Fig. 2). In case the trails were due to bright fireballs outside the field of view of the high-definition television, they would be recorded by the all-sky airglow imager. This instrument added to flux measurements with two of the SETI intensified cameras. In addition, *Electra* carried a slitless high-resolution meteor spectrograph, sponsored by NASA Ames Research Center and developed for this mission, and a small 11" University of East Anglia telescope that could be aimed at persistent trains for meteor train spectroscopy and that measured airglow emission. Both instruments targeted the bright meteors that were to be recorded by the all-sky imager.

The instrument layout of *FISTA* is shown in Fig. 3. All windows were on the right side of the aircraft. The near-IR and mid-IR spectrometers covered the wavelength range from 1 to 13 μm (Fig. 1) and was the first effort to study meteors and meteor trains in this spectral range. The high altitude enabled low water vapor content and low-IR backgrounds for highest sensitivity. The Aerospace Corporation's BASS mid-IR spectrometer (*e.g.*, Lynch *et al.*, 1992) was installed in the aircraft with an open port to the outside, trainable around an elevation of ~12°, where the highest incidence of

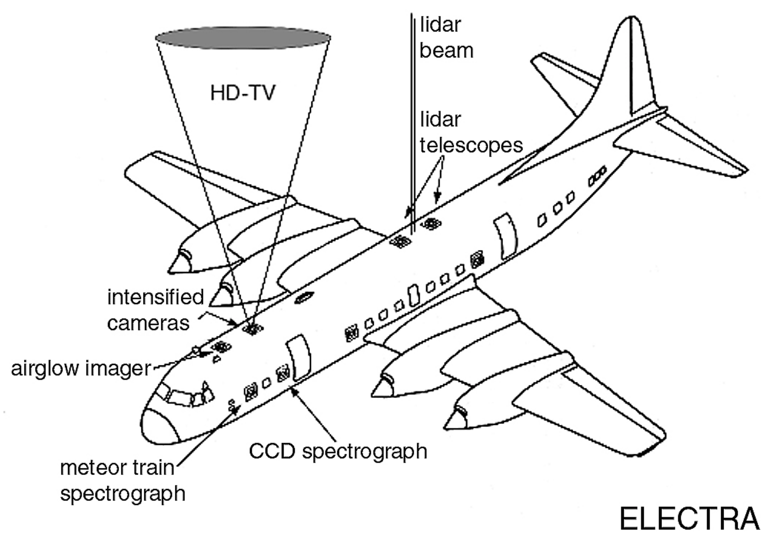

FIG. 2. Relative position of instruments on *Electra*.

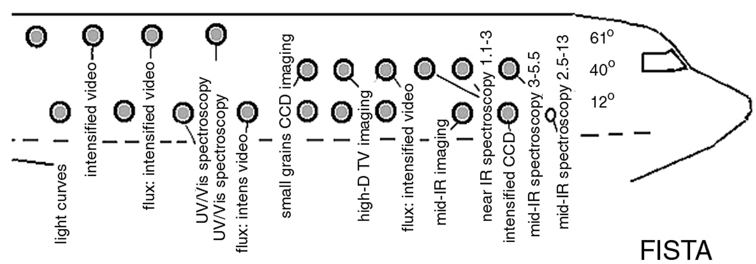

FIG. 3. Relative position of instruments on *FISTA*.

persistent trains was expected. The Air Force Research Laboratory's mid-IR camera was coaligned in an adjacent port to provide a broadband flux measure. The Aerospace Corporation's MIRIS spectrometer was mounted at the higher 40° port, using existing mounts, and coaligned with Air Force Research Laboratory's Bomen Michelson spectrometers to minimize water vapor absorption.

Research on *FISTA* also included newly developed techniques for television meteor spectroscopy (Borovicka and Bocek, 1995), CCD imaging, and a second high-definition television for stereoscopic observations, as well as numerous intensified cameras for flux measurements and the measurement of meteor light curves (Hawkes *et al.*, 1992). The SETI Institute's low-resolution ultra-violet/visible (UV/VIS) spectrometer was mounted in one of the high 61° ports to capture intrinsically faint meteors, whereas the Ondrejov Observatory UV/VIS spectrometer was operated from one of the low windows to capture intrinsically bright meteors. Flux measurements were performed at the 12 and 40° windows, whereas faint meteors were counted from the 61° window. The Mount Allison University intensified cameras studied meteor light curves from the high ports too, in order to study wake and fragmentation at highest spatial scales. Finally, the Kobe University CCD camera could be operated from both a 45 and a 61° window in order to be able to follow the rising (true) radiant during the night. These windows were coated with a broadband antireflection coating to avoid reflections from light within the cabin.

Each aircraft executed a significant experiment and a blend of techniques that addressed composition, morphology, and flux measurements, which would have provided sufficient justification for Leonid MAC in case one of the aircraft was grounded by mechanical problems. In order to guarantee results, some instruments were intended to gather useful data even during low meteor activity. Others were intended to benefit from the potentially high meteor flux.

Kadena Air Force Base in Okinawa was chosen as our base of operations because it was favorably located for highest fluxes, in eastern Asia and near +20° N latitude, and far enough west to be able to detect the storm before twilight would interfere at 21:00 UT (Fig. 4). However, some predictions suggested a time of the peak close to this time (Jenniskens, 1996). In order to be sure that the total flux profile would be covered, ground stations were established at two locations in the People's Republic of China, plus-one and plus-two timezones west of Okinawa (Fig. 4). Meteor observers of the Dutch Meteor Society established two double-station networks for measuring meteor trajectories and orbits and for flux measurements. Czech, Chinese, and U.S. (amateur) astronomers collaborated in the effort. The main sites were at the Xing Long Station of the Beijing Astronomical Observatory and at Qinhai Radio Observatory near Delingha in the Qinhai desert. The stereoscopic photographic and video observations would mainly target relatively bright meteors (less than +4 magnitude), whereas the high-definition television experiment on Leonid MAC targeted faint meteors (+4 to +8 magnitude). The ground effort was organized as a collaboration between the Dutch and Chinese Academy of Sciences and was supported by the Leonid MAC program.

Other ground-based efforts were set up by researchers participating in Leonid MAC. A double-station network was setup in California by members of the California Meteor Society. Additional efforts were made by the University of Kobe to study the faint glow of scattered sunlight from a location at Mauna Kea in Hawaii and from sites in

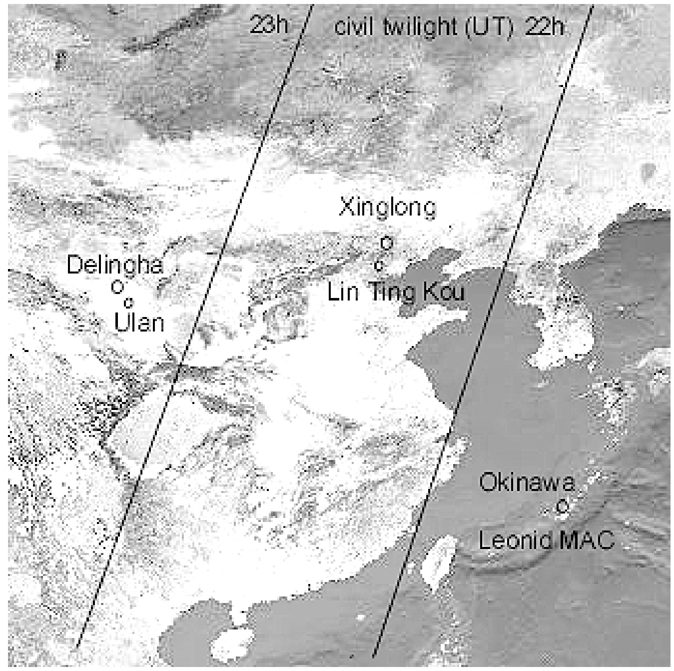

FIG. 4. Location of airborne campaign and related ground-based efforts in eastern Asia.

Japan, mainly in anticipation of potential vibration problems in the aircraft. And at the Starfire Optical Range at Kirtland AFB in New Mexico, a ground-based lidar experiment was performed in a collaborative effort between the University of Illinois, the University of Cornell, and the Starfire Optical Range, with participation of Utah State University, Aerospace Corporation, and NASA Ames. The Starfire Optical Range 3.5 m telescope made it possible to point a Na wind/temperature lidar and a green Cu-vapor laser to persistent trains by means of guiding cameras, an experiment not possible in Leonid MAC. In addition, airglow instrumentation collected data on airglow emissions and temperatures and meteor trail emissions (Na line).

This rather complex international and multiagency effort was organized by making use of the medium of the internet to provide frequent updates of the status of affairs to participating scientists and funding sources. For that purpose, a web site was maintained by the mission's principal investigator at NASA/Ames Research Center. A mirror site was established at Leiden University. The site also informed the general public about the Leonid shower and related observing activities worldwide. A separate mission web site was created prior to the mission itself for reporting some first results on mission day. The sites were accessed more than 400 000 times, for a total of 5.7 million hits, most of which occurred in the days surrounding the peak of the shower.

RESULTS

The mission proceeded much as planned. On the night of 1998 November 17/18, the *Electra* aircraft followed a predesigned pentagon-shaped route in a region southwest of Okinawa over Japanese and international waters (Fig. 5). The faster moving *FISTA* followed a similar flight pattern at ~120 km distance, and an effort was made to keep *Electra* at all times on the right side of the aircraft in view of the *FISTA* observers (note that *Electra* itself was not visible from the aircraft). *Electra*'s cruising altitude was 7 km,

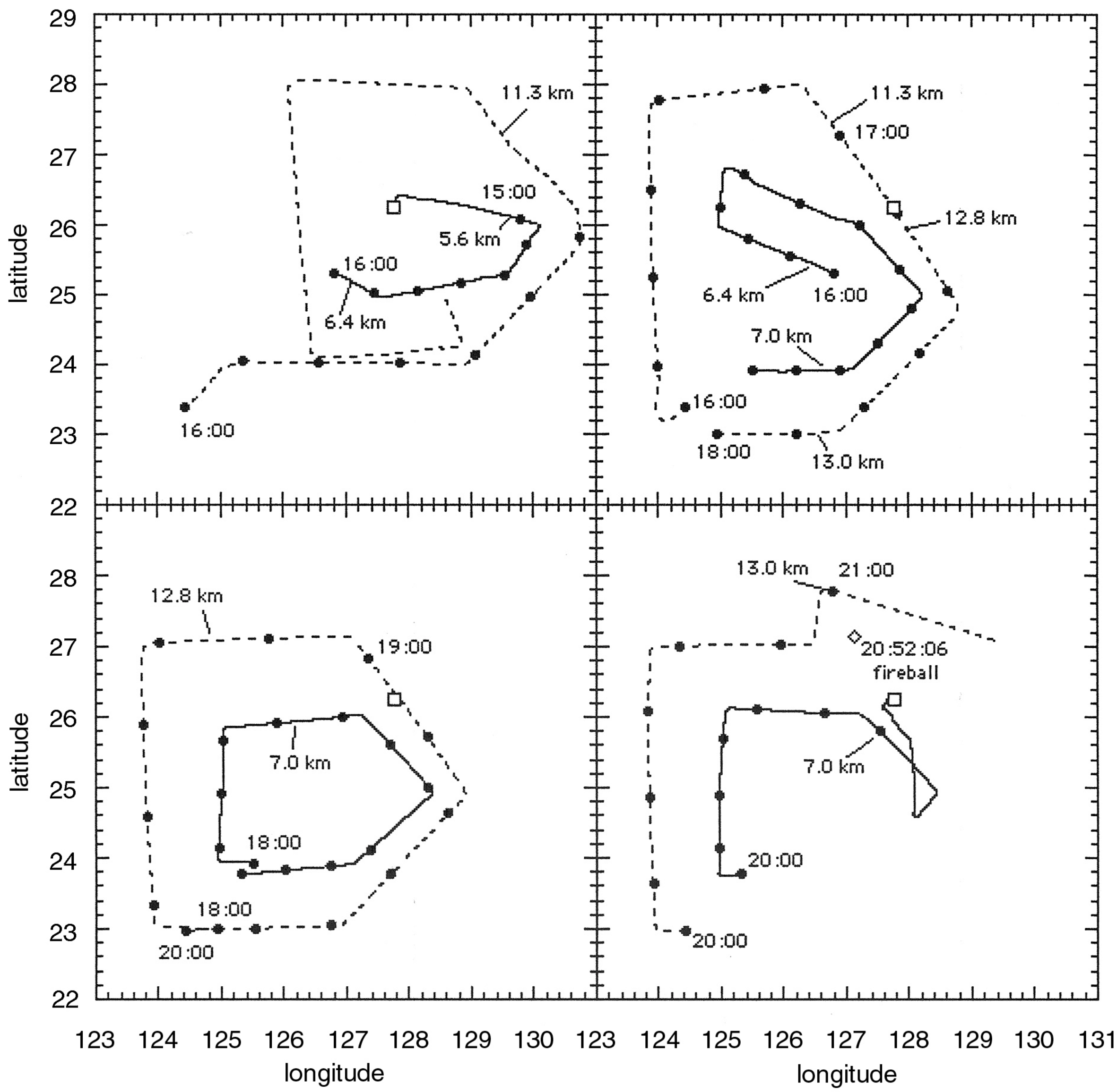

FIG. 5. Flight path of *Electra* (solid line) and *FISTA* (dashed line) on the night of 1998 November 17. Dots mark time in 10 min intervals. The square is the location of Kadena Air Force Base on Okinawa.

which put it just above the clouds for most of the night, except between 16:13 and 16:57 UT, when high-altitude clouds in the northern part of the projected flight path forced a decision to move the pentagon flight pattern south. The *FISTA* aircraft maintained a cruising altitude of 11 km early in the night, safely above clouds, and climbed to 13 km at 17:00 UT.

The mission itinerary consisted of the early departure of *FISTA* at ~13:45 UT (22:45 local time), followed by a one-hour period of unpacking instruments and their installation in front of the windows. All instruments were set up at ~15:00 UT when the radiant rose above the horizon. *Electra* departed at 14:30 UT. When the pentagon pattern was finally established at ~17:00 UT, there was still some difficulty in keeping the aircraft directions coaligned, which made stereoscopic observations difficult. Only at the center of each track were the aircraft well aligned (Fig. 5).

The observed Leonid meteor rate gradually increased during the night (Fig. 6). The first Leonid meteor was detected at 15:10:46 UT (when the true radiant was 2° above the horizon), followed by the first lidar debris trail at 15:45:54 UT. The low radiant caused long meteor streaks on the sky, until ~17:00 UT. At ~17:45 UT, a flurry of fireballs gave the first CCD spectra. The observed Leonid meteor rate gradually increased, with a maximum in the last hour of the night. As a result of staying close to Okinawa, the radiant elevation dilution of the meteor flux was similar to that from any ground-based observing site. At the end of the night, meteors were counted at a rate of 2–3 per minute through a large window on *Electra*. The magnitude distribution index varied little. Twilight started to interfere after 20:50 UT for the low cameras and after 21:00 UT for the high cameras. Observations were continued until ~21:10 UT.

A number of persistent trains were detected (Table 2). The main event of the night was the train of the 20:52:06 UT fireball, when a bright flash of scattered light was recorded by all intensified cameras. The fireball was seen by the *FISTA* pilots in front of the aircraft. The plane was quickly turned north to accommodate

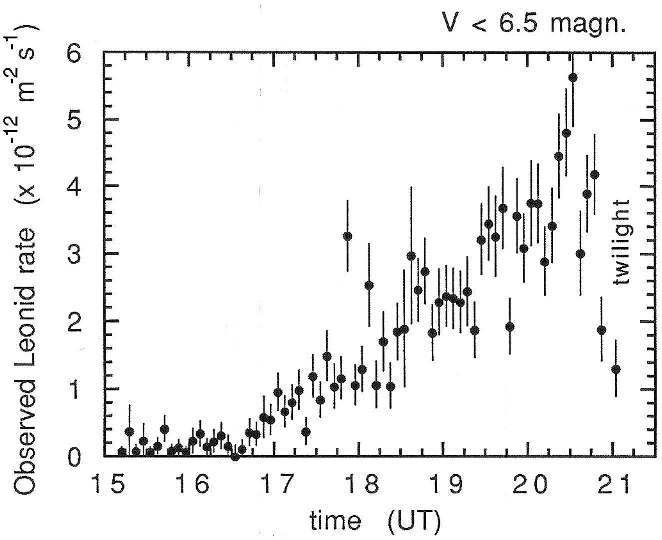

FIG. 6. Observed Leonid meteor rate on 1998 November 17 (no correction for radiant elevation).

observations from the right side of the aircraft (Fig. 5). Several other long-lasting trains appeared low on the horizon but were not recognized because the sky was not viewed at all times. The pointing cameras of the various trainable instruments typically did not cover all of the accessible hemisphere.

At the end of the night, ~3200 meteors had been recorded with the intensified cameras. One video camera caught the unusual image (Fig. 7) of a satellite that was seemingly hit by a (much closer) meteor in an uncanny coincidence of projection, a vivid example of the nature of the satellite impact hazard (note that no satellite anomalies were reported during this Leonid display). The first detections of meteors in the mid-IR were on tape, and over a hundred low-resolution visible/near-IR spectra of Leonid meteors were obtained as well as a small number of high-resolution spectra. These were the first such measurements for Leonid meteors. Eighteen debris trails were detected by lidar, some positively identified with meteors recorded by the high-definition television camera. Numerous persistent trains were on record. For the first time, a spectrograph was successfully trained at a persistent train. Detailed images of such trains for the first time showed turbulent structure in the perturbed air. And the first deep wide-field images of the true radiant were ready for analysis.

Various ground-based efforts were successful too. Clear nights in China resulted in numerous orbits and trajectories of meteors. The meteoroid cloud was detected from Hawaii. A number of long lasting persistent trains were successfully probed by the University of Illinois Na lidar and imaged in great detail. The site had clear weather during the night of November 16/17 when numerous fireballs were observed. Leonid persistent trains could be probed for as much as an hour during the night. On the other hand, photographic efforts in California and several other ground-based observations in the USA and Europe were not successful, because of bad weather.

DISCUSSION

At the time of writing, only part of the data has been reduced. This issue of *Meteoritics & Planetary Science* contains some of the first results presented at the 1999 April Leonid MAC workshop (Rietmeijer, 1999). The science objectives of the mission were as broad as the array of instruments fielded and the interests of the participating scientists. In general terms, they touched on open questions in astrobiology, planetary astronomy, the satellite impact hazard, and the atmospheric sciences. Many of these contemporary science issues are interdisciplinary in nature and relevant to more than one field.

Science Issues in Astrobiology

Many experiments addressed issues that are relevant to the new field of astrobiology. In the quest to understand the prebiotic evolution of life, it is important to consider meteoroids as a source of organic matter and metallic compounds, next to the water and other materials supplied by violent comet impacts to the Earth during late bombardment (*e.g.,* Thomas *et al.,* 1998). Meteoroids and small asteroids account for most matter accreting onto Earth, and nearly all of that ends up in some ablated form in the atmosphere (Ceplecha, 1992; Love and Brownlee, 1993).

TABLE 2. Leonid fireballs and persistent trains detected on 1998 November 17.

Time	Mv*	Stream	Train duration (min)		Elevation (degrees)	*Electra*	Elevation (degrees)	*FISTA*
16:47:46	(–3)	Leo	0.05		–		6	FL50F
17:39:35	(–4)	Leo	3	39:35–42:30	–		12	FL50F
17:44:45	(–4)	Leo	>1	44:45–45:27	–		6	FL50F, FH55F
17:47:13	–4	Leo	–	bright part outside field of view	–	(ECCD)	67	FH20, UVVIS, FH50F
18:06:17	–9	Leo	22	07:43–28:30†	–	(E50F)	4	FL50F, FL20, FL50R
18:08:47	–5	Leo	–	train outside field of view	–	(ECCD)	–	
18:16:08	(–4)	Leo	–	low in clouds	–		3	FL50R
18:17:43	(–4)	Leo	2	17:43–19:40	31	E50R	10	FL50R
18:48:08	–5.5	Leo	5.5	48:08–53:30	–		5	FL50R, FH20, FL20
18:57:12	–4	Leo	–	low on horizon	–		2	FL50R (while turning), FL20
19:26:04	–2.5	Leo	0.05		28	E50R	25	FH20, FL20, FL50R
19:33:26	–4	Leo	0.2	33:26–33:36	–		23	FL50F, FH20, FL20, FH55F
19:42:31	–4	Leo	0.15		–		38	FH50R, FL20, FL50F
19:56:49	–4	Leo	0.5		–		35	FH20, FH50R, FL20, (FL50R)
20:07:36	–3.5	Leo	0.08		–		26	FH20, FL50R, FL20
20:25:51	–3.5	Leo	1	25:51–26:50	–		34	FL50F, FH20, FL20
20:33:12	–5.5	Leo	–	outside field of view	–		2	FL20
20:52:06	(–10)	Leo	>11	52:53–03:11	29	(ECCD)	48	FL50F, FH50R, FH50F

*Mv = absolute visual magnitude. †Meteor itself not observed

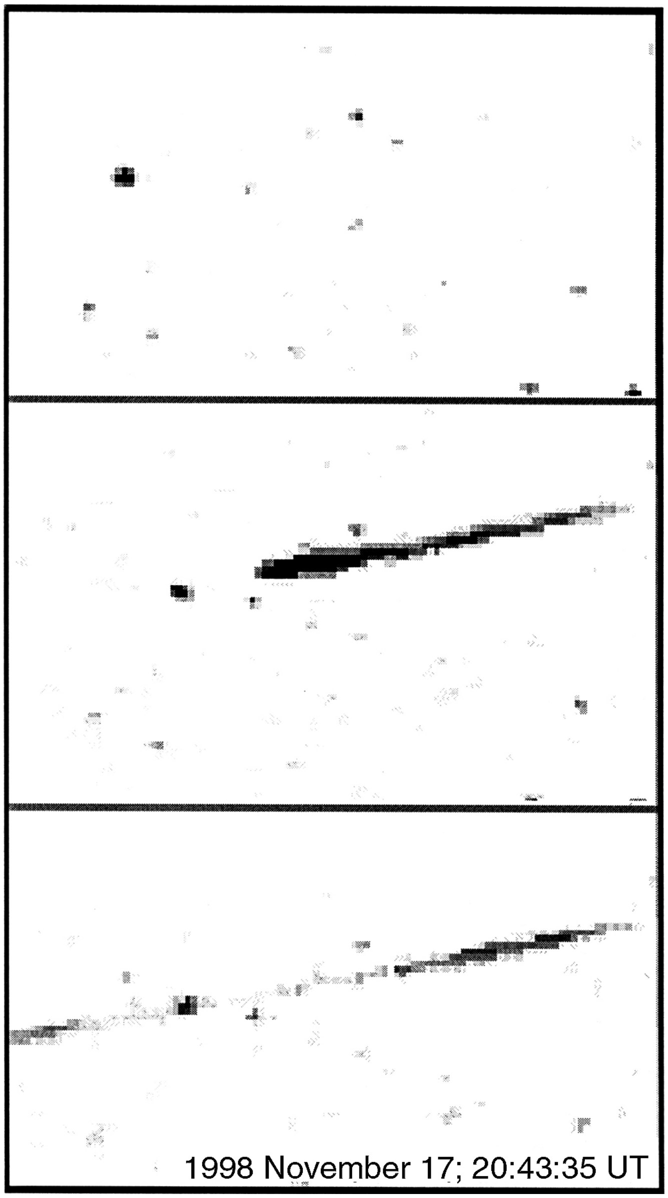

FIG. 7. A meteor is seen to pass over the image of a passing satellite. Three frames from this rare video illustrate the nature of the satellite impact hazard. The video was taken from *FISTA* with the Mount Allison University's 50 mm intensified camera (image 7° across) by Ian Murray. A persistent train remains visible in the path of the meteor shortly after it has passed (bottom frame).

Meteoroids can potentially provide a steady influx of reduced metallic compounds, which can be a catalyst of organic chemistry, and a steady influx of organic molecules—the building blocks of life. Moreover, meteors induce shock synthesis in the atmosphere, which can lead to significant amounts of reduced N and C compounds in certain types of atmospheres (Chyba and Sagan, 1992; Chang, 1993). Surprisingly little is known about the physical conditions in ordinary meteors and the efficiency of induced atmospheric chemistry, the content of organic matter in large meteoroids, the fate of ablated materials in the Earth's atmosphere, and the formation of meteoric debris particles and recondensed vapor. For these reasons, and with support of NASA's exobiology program and the Astrobiology Advanced Missions and Technologies program, the 1998 Leonid MAC became NASA's first astrobiology mission.

The Leonid MAC set out to obtain the first spectroscopic data on molecular bands from excited atmospheric compounds (N_2, NO, OH) and meteoroid ablation products (C_2, CN). Our goal was to measure the excitation conditions in the meteor's path and determine the presence of organic matter in large meteoroids (Jenniskens *et al.*, 1999). We found to our surprise that the spectra of mangitude –5 to +3 Leonid meteors had unusually strong rovibrational bands of N_2. For the first time, such bands were observed at high enough resolution to infer rotational temperatures, refining the physical conditions for meteor-induced chemistry and meteor ablation in a range of atmospheres (Jenniskens *et al.*, unpubl. data). This data adds to information on the physical properties of meteoric plasmas in larger fireballs of cometary origin that can be derived from the infrasonic boom detected at Los Alamos in New Mexico by Revelle and Whitaker (1999).

We did not detect the expected signature of organic matter. However, Spurny *et al.* (2000) derived extreme beginning altitudes for some bright fireballs (a record 199 km for a 1 kg Leonid) and measured unusual light curves with a sudden onset of ablation at 120 km altitude, when silicates are expected to start ablating. The Leonid light curves, their fragmentation behavior, and the extreme beginning altitudes are indirect evidence for a volatile component that keeps the meteoroid fragments together but is quickly lost during entry. It has been speculated that Na-containing minerals may be responsible, given the early ablation of Na (see below). However, a more likely candidate is complex organic matter, which is expected to be present in cometary meteoroids. Perhaps much of the organics is lost at high altitude, where the meteors are too faint for spectroscopic analysis (Steel, 1998). Alternatively, the organic matter may be ablated in the form of a wide range of large molecules rather than the more easily detectable C_2 and CN fragments. The key is the nonequilibrium process of evaporation, analog to laser-induced evaporation of PAH molecules in two-stage mass spectroscopy. The flash heating of meteoroids may be sufficiently nonequilibrium for large fragments to rapidly cool in the flow of cold air.

Complex organics are potentially detectable in the mid-IR, where the C–H stretch vibration and other organic emission bands are found. No mid-IR spectra were obtained this year, but the analysis of results so far suggests that such observations are within reach. Rossano *et al.* (1999, unpubl. data) reported at the Leonid MAC workshop the first detection of meteors in the mid-IR from fairly faint meteors, which suggests that a spectrum could be detected if only a meteor of magnitude 0 would cross the field of view of the current spectrograph.

Science Issues in Planetary Astronomy

The meteoroids themselves probe the main element composition of comets and the morphology of large cometary grains (after the ice has evaporated). Hence, the Leonid MAC, supported by NASA's Planetary Astronomy Program, can be viewed as a poor-man's comet mission. Borovicka *et al.* (1999) recorded many low-resolution spectra that give a detailed picture of the ablation of metal atoms from large meteoroids. For the first time, differential ablation of the metals Na and Mg was detected, a process ascribed to fragmentation, the Leonids being much more fragile than other shower meteoroids. Confirmation of such effect comes from ground-based lidar observations of Leonid meteors probing different neutral atoms in work by von Zahn *et al.* (1999) in Kuelungsborn, Germany. Spurny *et al.* (2000) was able to measure key physical parameters of fast Leonid meteoroids from bright fireballs observed from the ground and concluded that the Leonid meteors seen during the 1998 outburst were of type IIIb, the most fragile of meteoroids, and derived a density of 0.7 g/cm^3. Finally, Murray *et al.* (1999) showed that the light curves of the meteors can only be understood if the Leonid meteoroids are crumbling dust balls when entering the atmosphere. The fragile nature of fresh cometary ejecta is consistent with the fragile morphology of the dust in the coma of comet P/Halley, in the mass range 10^{-11} to 10^{-4} g (*e.g.*, Greenberg and Hage, 1990; Donn, 1991). The fragile morphology has now been demonstrated also for the heavier grains, on the order of 10^{-5} to 10^3 g (submillimeter to cemtimeter size range), that carry most of the mass loss of comets and that are a source of zodiacal dust.

Because of this significance of large grain ejecta, the field of planetary astronomy has a vested interest in studies of meteoroid stream dynamics. A discussion of open questions is given in Jenniskens (1998). Each recent return of the Leonid shower has provided a new scan of the distribution of large dust grains in the vicinity of the comet. The 1998 return led to particularly detailed observations of the flux curve (Jenniskens, 1999) and the distribution of orbital elements (Betlem *et al.,* 1999). The observations provide especially detailed insight into a broad component of bright meteors that was detected first in 1994 and is now thought to originate from meteoroids trapped in orbital resonances (Asher *et al.,* 1999). Some evidence for this was found in Betlem *et al.* (1999). This component peaked earlier than expected, but much as during the 1965 return. In addition, the observations showed a second concentration of dust near the comet node. This feature turned out to be unusually asymmetric (Jenniskens, 1999) and has now been interpreted as a composition of signatures from individual debris trails, confirming recent computational evidence that individual debris trails may be recognized in the flux curve (Asher, 1999).

Several meteoroids as large as 1 kg (–14 magnitude) have been detected (Spurny *et al*., 2000), but no Leonid meteors brighter than magnitude –16. Whipple's equation for dust ejection by water drag predicts that the largest possible meteoroid that can be lifted from the comet surface would have a diameter of ~20 cm and weigh ~3 kg. The lack of truly spectacular fireballs is consistent with this theory. This confirmation is important for understanding the boulder environment of say comet Wirtanen, which will be visited by the *Rosetta* spacecraft (Fulle, 1997).

Due to lack of a meteor storm, we were not able to measure the width of a single dust trail as a function of particle size, although Jenniskens (1999) provides tentative evidence of such effect in the data that were obtained. In principle, such data provide a direct measure of the mass-dependence of ejection velocities for large grains, a fundamental parameter in models of meteoroid stream formation and evolution. There is good hope that more useful measurements will be possible during the 1999 return of the Leonids. Recent models by Asher (1999) suggest that the Earth in 1999, unlike the previous year, will pass close to a dust trail ejected in 1899. This is the same trail responsible for the 1966 storm. Hence, the 1999 return may provide an important second path through the same dust trail.

Issues Related to the Satellite Impact Hazard

Predicting meteor storms is of direct relevance to addressing the satellite impact hazard. Meteor storms are a significant anomaly in the natural meteoroid influx, the background sporadic meteors, both in frequency as in directionality and in velocity space. The prospect of a meteor storm during the 1993 return of the Perseids, in association with the 1992 return of comet 109P/Swift–Tuttle (Beech and Brown, 1994; Beech *et al.,* 1995, 1997), and a malfunction of ESA's *Olympus* satellite at the time of the meteor outburst (Casswell *et al*., 1995), led to the realization that satellites are potentially at risk from meteor storms. There was considerable caution during the 1998 Leonid return. The U.S. Air Force/Space Command, in a project lead by the Aerospace Corporation, was making an effort to gather all housekeeping information on satellites during the return of the showers and provide a near-real time meteor flux awareness. As a result, various agencies within the U.S. Air Force provided logistic support that made the Leonid MAC effort possible. This included hosting the two Leonid MAC aircraft at Kadena Air Force Base on Okinawa.

The observed peak of the shower was unlike that of predictions by early models of Brown and Jones (1993) and Wu and Williams (1996), and it has since been realized that accurate peak timing can only be achieved by examining dust trail models at small spatial scales (*e.g.,* Asher, 1999).

Of interest to the satellite impact hazard are also near-real time flux measurements and the size distribution towards faint meteors. The high-definition television observations were set up to measure the flux of faint meteors. Overall, there was a lack of faint meteors in the shower (Yano *et al*., unpubl. data; see also Pawlowski, 1999). This lowers the danger for plasma generation for a given satellite, because the small grains are usually the more abundant and more likely to impact. However, this is not the whole story. Nakamura *et al*. (unpubl. data) reported at the Leonid MAC workshop the detection of scattered sunlight off dust particles in the Leonid meteoroid stream in observations from ground locations in Hawaii. The meteoroid cloud is a feature reported prior only in anecdotes from the 1833 storm (Gadsen, 1980). This data will provide spatial information on the dust distribution in dimensions perpendicular to Earth's orbit, which are not accessible by meteor observations in a single return of the comet. The scattering is efficient only for small, <100 μm-sized grains, which appear to be more abundant than expected. Those abundant smaller grains may reside in orbits that do not intersect Earth's orbit in this return but pose a threat in future encounters.

Precise flux measurements of brighter meteors were obtained with the SETI Institute intensified cameras (Jenniskens, 1999). It turned out that the low atmospheric absorption at the altitude of the aircraft platform permitted measuring meteors at larger distances and lower elevation angles than would be possible from ground-based sites. The meteor flux measurements need to be calibrated to mass influx, which demands an understanding of the relationship between meteor luminosity and meteoroid mass. The lidar observations of the neutral Fe debris trails (Xu *et al*., unpubl. data), in combination with optical imaging, are expected to lead to an *in situ* calibration of luminosity and mass. These data are still being analyzed.

Science Issues in the Atmospheric Sciences

That brings us to the final field of research: the upper atmosphere sciences. Meteor storms are the only perceivable anomaly in meteoroid influx for reaction chemistry type experiments. The neutral atomic debris background can be disturbed if the small meteoroid influx increases, whereas large meteoroids can cause an increase in the incidence of neutral atom debris trails. Both can be studied as a function of time by means of lidar observations (*e.g.,* Kane and Gardner, 1993). The measured lifetimes would provide data on molecular diffusion and chemical reaction rates of neutral atoms in the upper atmosphere (*e.g.*, Cox *et al.*, 1993; Höffner *et al.*, 1999). For these reasons, atmospheric scientists of the University of Illinois and the University of East Anglia (U.K.) participated in the mission and the National Science Foundation provided logistic support to Leonid MAC.

It was reported at the Leonid MAC workshop that the lifetimes of the observed debris trains were much longer than expected (Xu *et al.*, unpubl. data). No obvious enhancement of the neutral atom debris layer was observed at the expected altitude in the Fe-lidar data from *Electra.* Di Carlo *et al.* (unpubl. data) reported a tentative identification of such layer in Na in lidar observations from de L'Aquila, Italy.

Another topic of interest to atmospheric scientists is the luminescent mechanism of persistent trains (*e.g.*, Baggaley, 1980), which has not been established with certainty (Borovicka *et al.*, 1996). In fact, even the reason why Leonid meteors are so abundant in long-lasting (5–30 min) persistent trains is a mystery. For the first time, high-resolution images of persistent trains have been obtained, and trains have been probed by lidar and near-IR spectrographs. It was discovered that long-lasting persistent trains tend to be hollow, cylindrical structures. It is not known what causes the lack of luminosity in the center of the train. Some trains stand out because of strong billowing, the cause of which is also unknown. The dynamics of train evolution, the location of Na atoms in the train, and the observed emission are expected to address these issues of meteor train dynamics.

Of particular interest is whether the insertion of O atoms by the meteor enhances the natural airglow chemistry (Zinn *et al.*, 1999) or that only meteoric metals play a role in the catalyis of O and O_3 (Baggaley, 1980). The near-IR observations of the 20:52:06 UT train from *FISTA* (Kristl *et al.*, unpubl. data) may shed further light on this issue. We did not succeed in securing high-resolution visual spectroscopic data of persistent trains. Japanese observers Abe *et al.* (unpubl. data) reported at the Leonid MAC workshop the detection of a low-resolution spectrum of a Leonid persistent train, which is similar to the spectrum of a bright Perseid train by Borovicka *et al.* (1996), but they arrive at a quite different line identification.

Finally, the expected existence of meteoric debris and recondensed vapor (*e.g.*, Dean Fyfe and Hawkes, 1986; Kelley *et al.*, 1998) remains an intriguing possibility that awaits confirmation. As far as we understand now, no debris particles or recondensed meteoric vapor particles were detected. The various lidars did not detect scattered light from particles in individual debris trails, and the mid-IR cameras did not pick up long-lasting emissions of warm dust. It is not known yet how strong an upper limit was set by the observations.

IMPLICATIONS FOR FUTURE MISSIONS

A future mission has to continue where the 1998 Leonid MAC left off. It is clear that mid-IR and near-IR imaging and spectroscopic techniques have still much to reveal. The detection of organic matter in meteoroids and the detection of recondensed meteoric vapor remain elusive. On the other hand, Leonid meteors turn out to be very useful for the study of meteoric plasmas, and abundant persistent trains provide ample opportunity to probe the gas and dust in the path of bright meteors.

Based on experiences during the 1998 Leonid MAC, we find that much improved mid-IR observations can be made by deploying the same spectrometers on *FISTA* in different observing mode and with improved sensors. The 3–5.5 μm regime is of interest for detecting the C–H stretch emission of compex organic molecules, perhaps the only way to detect ablation of large molecules. The unexplored 0.3–0.45 μm near-UV and 1–3 μm near-IR spectra of meteors may reveal the elusive C_2 and CN band emission.

In addition, more powerful mid-IR imaging techniques may reveal whether (fragile Leonid) meteoroids leave behind intact particles or if meteor vapor recondenses in warm debris in the wake of the meteor.

The logistic effort of a Leonid MAC can be improved by raising awareness of bright meteors in the sky. A spotter camera and a more ready way of communication between the researchers is called for. If two aircraft of similar design are flown, then it is possible to follow a westward trajectory. This would serve to extend the night and improve the general observing conditions, as well as make it easier to perform stereoscopic observations.

A new airborne campaign is being prepared. The 1999 Leonid MAC will be flown over Europe or Africa for best viewing. Modelers seem to agree that chances are good to encounter a (relatively low-intensity) meteor storm, peaking shortly after 2:00 UT on November 18. Our mission web site (connected through the NASA-OSS current and past missions site) will provide further information and periodic status reports while the 1999 campaign develops.

The 1998 Leonid MAC was a very successful endeavor. It had a positive and ambitious attitude of exploration and resulted in significant new insights into several scientific areas. Its influence went beyond the participating researchers, by motivating (amateur) researchers worldwide with their efforts in ground-based observations of the shower. We anticipate at least as exciting a mission in 1999 November and hope that, better prepared now, we will finally see the recent ejecta that is the cause of meteor storms.

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Mr. Noriyoshi Miyazaki, staff reporter Noriyuki Mizuno, and News America producer Mr. Yuichiro Ando. Coordination of outreach activities at NASA Ames Research Center was in the hands of Greg Schmidt, Kathleen Burton, Ed Schilling, Kathleen Connell, and Frankie Ridolfi. The SETI Institute provided logistic support for the participating scientists and overall coordination. Special thanks goes to contracts and procurement manager Hal Roey, grants specialist Brenda Simmons, and project resources coordinator Debbie Kolyer. The ground-based efforts were coordinated by Hans Betlem and Marc de Lignie of the Dutch Meteor Society, the Netherlands, and by Li Guangyu of Purple Mountain Observatory and Zhu Jin of Beijing Astronomical Observatory, People's Republic of China. The Starfire Optical Range effort was coordinated by Chet Gardner of the University of Illinois and by Mike Kelley of Cornell University and Jack Drummond of the Starfire Optical Range at Kirtland Air Force Base. National Aeronautics and Space Administration's Planetary Astronomy program took the leading role in enabling the mission but other funding organizations had to step in to make the mission possible. The 1998 Leonid MAC was sponsored by NASA's Planetary Astronomy Program, NASA's exobiology program, the NASA/Ames Research Center, and the NASA/ARC Astrobiology Advanced Missions and Technologies Program for Astrobiology. The Kobe University effort was supported by the Air Force Office of Scientific Research (AFOSR)–Asian Office. Dr. Sherwood Chang, now retired branch chief at the Exobiology Branch of the Space Science Division of NASA Ames Research Center, Lynn Harper, the colead of the Astrobiology Advanced Missions and Technology program, and the NASA/ARC center director Dr. Henry McDonnald, helped secure the funding support at NASA/ARC. Our special thanks goes to Carl Gillespie, Ray Russell, and Chet Gardner, whose early and persistant support made this mission possible.

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