Proceedings SOFIA Upper Deck Science Opportunities Workshop, NASA Ames Research Center, Moffett Field, CA, June 22-23, 2004.

RESEARCH WITH AIRBORNE OBSERVATIONS AT 1000 FRAMES/S

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ABSTRACT

Recent advances in high time resolution imaging have revealed new and unexpected features in meteors and sprites. The SOFIA B-747 offers unique opportunities for detailed observations unimpeded by troposphere weather. In meteors a several 100 m scale size shock-like structure has been observed in bright Leonid meteors. The first observation was made in 2000 from Alaska and confirmation was obtained during the 2002 Leonid Multi-Instrument Aircraft Campaign. The causal process is uncertain. Our initial guess was a photo-ionization front and a computer model using standard oxygen chemistry can indeed reproduce the observed structure. However, the model is energetically impossible, and we are now investigating minor species as alternative. In sprites observations at 1000 fps have revealed distinct processes operating on time scales from <1 ms to >100 ms. The faster features (elves, halo, and sprite tendrils) appear to be driven by electromagnetic and electrostatic forces, but the processes leading to the slower features (blue jets, beads, crawlers, palm trees, etc.) are not at all known. Additional spectroscopic (at better than ms time resolution) observations of both meteors and sprites would be highly desirable and efforts in that direction are currently underway.

INTRODUCTION

Low light-level imaging has for decades been a major part of auroral research at the Geophysical Institute, University of Alaska Fairbanks, and the development of suitable imagers has been part of this effort. The image recording technology used has primarily been based on broadcasting video equipment operating at 30 frames per second. Although digital image processing was used extensively, the primary data were recorded on video tape. However, there are science problems that require higher time resolution and in 1998 we constructed a fully digital low light-level imager capable of recording up to 1000 frames per second. In addition to its original use in auroral research the imager has been remarkably successful in recording meteors and sprites with millisecond temporal resolution. The material presented here will draw from these observations.

The imager is an intensified CCD recording to the disk of the controlling computer. The images are 256x256 pixels at 8 bit (256 gray levels). To provide for the necessary CCD read-out speed each quadrant of the CCD are read out through separate electronics. Because of small differences in the read-out electronics the effective gain may at times differ slightly between quadrants which may be visible in the recorded images. With our standard 105 mm f/0.75 Old Delfte lens the field of view is 6.4x6.4 degrees. The instrument responds to light at wavelengths 500-900 nm with maximum sensitivity at 700 nm. The gain can be controlled externally, but all recordings reported on here were made at maximum gain. The frame rate is variable up to a maximum of 1000 fps at which rate (and at maximum gain) the images saturate at 3 MR.

SPRITES

Sprites are optical emissions observed in the mesosphere above lightning and they are initiated primarily by positive cloud to ground strikes. Images of sprites have been made using various video camera systems, but the 30 fps data rate of video is not sufficient to resolve the temporal development of sprites. 1000 fps sprite recordings have revealed many new details of sprites (Stenbaek-Nielsen et al., 2000), but even ms time resolution is not high enough to resolve the initial phases of a sprite event. Nevertheless, the imager has provided spectacular images of sprites.

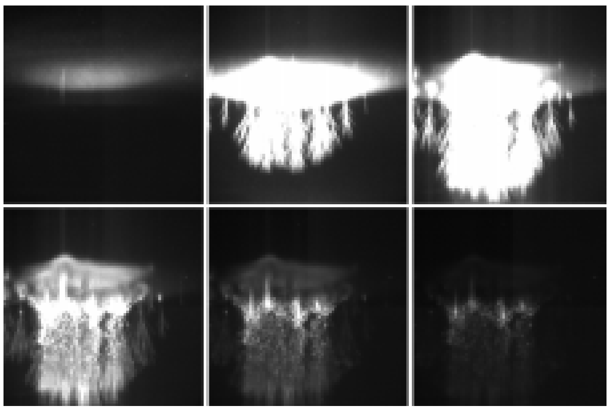

Fig. 1: Large sprite. Each image 1 ms apart.

Figure 1 shows a large sprite observed from WIRO, Wyoming, on 18 August 1999 above a thunderstorm over Nebraska. This event only lasts 6 ms. A more typical duration is 10-30 ms, and at times the event is followed by less obvious activity for several 100 ms. The figure shows some typical sprite features: The large, relatively featureless structure prominent in the first image is the sprite halo at an altitude of 70-80 km. The sprite halo appears within a few ms of the causal lightning strike. Prior to the halo there may be an elve (not visible in this event), which is a very short lived, doughnut shaped airglow emission from an altitude of 90-100 km caused by an electromagnetic pulse emanating from the lightning strike below (Barrington-Leigh at al., 2000). The main sprite event follows the halo with tendrils going down and branches going up. The propagation velocities of the tendrils are often large, ~50,000 km/s. The bottom of the tendrils in figure 1 is at an altitude of 37 km and the top of the branches is at 94 km. The horizontal extent is about 80 km. Assuming the event to be cylindrical the horizontal cross section would be about 700 km^2. Most sprites are considerably smaller.

The optical emissions from the sprite in figure 1 fade rapidly, but in many sprites the bright beads embedded in the central and lower portion may linger on for several 100 ms. Often the beads will activated sporadically and they may move slowly in the images plane. This indicates that processes initiated in the initial sprite formation may continue and may leave an imprint on the background atmosphere. Evidence of this is seen in figure 2 where the volume occupied by the first sprite re-activates when a sprite is formed nearby.

Figures 1 and 2 only show a few aspects of sprites. Many more morphological types have been presented in the literature. Example are “blue jets” which move up from the top of the thunder clouds, “palm trees”, small sprite like structures also near the cloud tops, “ambers”, “crawlers”, etc. Figure 3 (courtesy Dave Sentman) is an attempt to illustrate the spatial relationship between various observed sprite features.

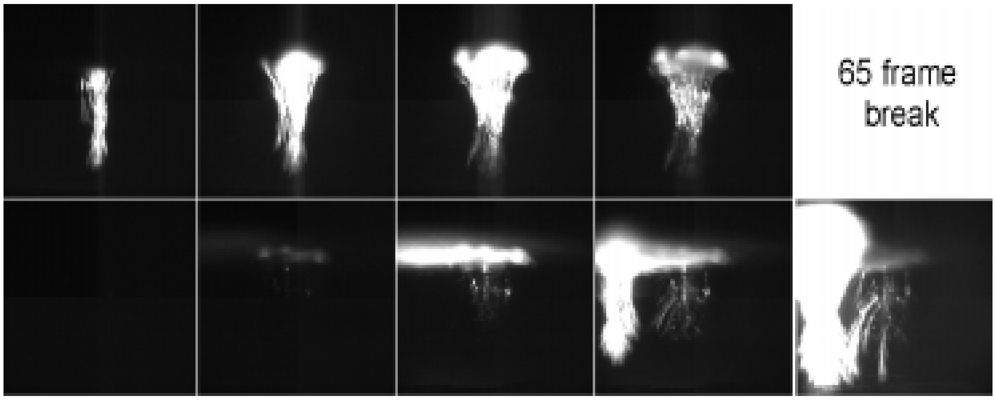

Fig. 2: Reactivation of old sprite region

A detailed physical understanding of the processes involved is still lacking. It appears that the elve is due to airglow generated by the electromagnetic pulse propagating up from the lightning strike (Barrington-Leigh et al., 2000). The halo is from an electric glow discharge and the branches and tendrils are from electric streamer discharges both driven by the electric field related to the lightning strike below. Although many details are uncertain, the theoretical framework proposed by Pasko in a number of papers (e.g. Pasko et al., 1997) seems promising. Much more uncertain are the processes associated with beads, jets, crawlers etc. These features do not appear to be directly driven by individual lightning strikes. In particular for the beads processes, likely chemical in nature, internal to the mesosphere may be involved.

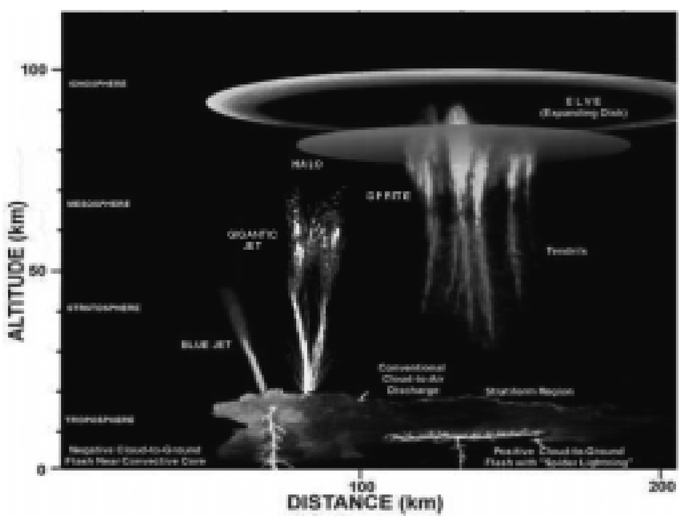

Fig. 3: Observed Sprite types

Progress is being made, but a very fundamental question has not been answered: Does sprite activity significantly impact the mesosphere? If so, sprites may affect the coupling between the upper and lower atmosphere, and this would be of critical importance to the global understanding of the atmosphere. Or phrasing the question another way: Are sprites like the rainbow, pretty to look at, but of no significance beyond that?

LEONID METEORS

High speed imaging has revealed a parabolic structure several 100 m across associated with bright, ~magnitude -3, meteors. The first observation was made during the 2001 Leonid shower (Stenbaek-Nielsen and Jenniskens, 2000) and 2 more examples were found in the Leonids observed the following year. These observations were made as part of the Leonid Multi-Instrument Aircraft Campaign. Figure 4 shows selected ms images from the first example. The shock-like structure forms at an altitude of 111 km and grows in size to the end of the high speed imager sequence at an altitude of 104 km. The examples recorded in 2002 were not as spectacular, but clearly had some of the same features indicating that the 2001 example is not unique.

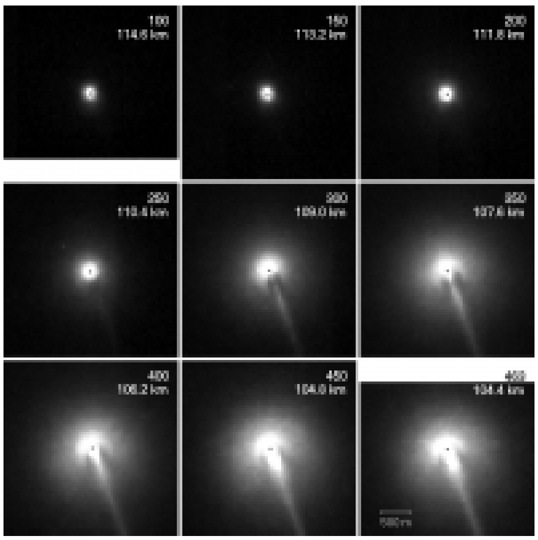

Fig. 4: Selected images from the 2001 Leonid

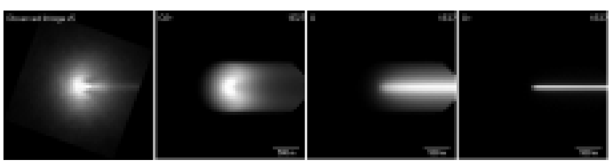

Fig. 5: Observe, O2 ion, O, and Oplus

The physical process leading to the shock-like structure is not known. The structure cannot be a classical fluid shock around the meteor as this would imply a meteor body very much larger than the ~1g, pea sized body commonly assumed responsible for a -2 magnitude meteor (R. Baker, private communication, 2001). Plasma instabilities also seem unlikely because the small mean free path at these altitudes. However, the Leonid velocity vector in the 2001 event, in which the structure was better developed, was almost perpendicular to the local geomagnetic field in contrast to the 2002 events, and hence, processes involving the geomagnetic field should not be ruled out.

One suggestion for a process is that the structure is due to photo ionization or dissociation driven by emissions from the hot meteor body. Qualitatively, this idea fits with the observation that the shock-like structure expands as the meteor get brighter and presumably hotter. Figure 5 shows output from a model simulating a photon source moving through the atmosphere at 71 km/s. The model assumes standard oxygen photo chemistry. Near the meteor UV photons will fully ionize and dissociate the ambient atmospheric molecular oxygen creating a parabolic front around the meteor very similar to what is observed. The width of the parabola depends on the assumed photon flux emanating from the meteor. The images from left to right are: The actual observation, followed by model line-of-sight integrated density of molecular oxygen ions, atomic oxygen, and atomic oxygen ions, respectively. But while the model clearly produces results similar to the observations it is not feasible since it requires an unrealistically large photon flux. We are now evaluating if other processes, for example involving minor species, would work.

IMPLICATIONS FOR SOFIA UPPER DECK INITIATIVE

The SOFIA Upper Deck Initiative can provide important opportunities for acquiring more high time resolution data on both sprites and meteors. Observations can be made above the clouds and the thinner atmosphere provides better general "seeing". For sprite observations concerns might be raised about fight safety, but the ideal distance from the active thunderstorms would be 500-700 km which would position the aircraft safely away from the activity itself. The high speed imaging equipment described in this paper has successfully been flown on aircraft. Of particular interest and importance is spectral information as this would likely identify the processes involved. Both the meteor and the sprite images indicate that the objects are sufficiently bright that spectra may be obtained even with millisecond resolution. We are currently adapting the high speed imager to a large aperture spectrograph which will be fielded in a sprite campaign scheduled for August 2004.

The high speed meteor recordings were made with the camera view direction fixed, and only storms like the recent Leonid showers will have enough meteors to ensure the recording of a reasonable number of events given the small (6x6 degree) field of view. During the 2002 Leonid shower the high speed imager recorded a total of 62 Leonids. However, technology now exists to improve on this. Imager technology will allow larger field of view without compromising spatial resolution (more pixels in the images), but a more important development is that rapid moving mirrors may be used to track the meteors. This technology (AIMIT) was proven on the recent Leonid MAC flights, and in November 2003 AIMIT was combined with the high speed imager to produce a number of meteor recordings. The track was established within about 100 ms from detection of a meteor with a large field of view video imager. For an investigation of the large shock-like structure this would be sufficient as the structure will only develop deeper into the atmosphere. Although the combined instrument is not fully developed, the technology has been proven and an instrument can be built for routine observations from for example SOFIA.

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Manuscript received 2004 June 18; accepted 2004 June 18.