Nadir observations of sprites from the International Space Station

Article *in* Journal of Geophysical Research Atmospheres · February 2004

DOI: 10.1029/2003JA009972

Elisabeth Blanc
Atomic Energy and Alternative Energies Commission

Thomas Farges
Atomic Energy and Alternative Energies Commission

Trung Hua
French National Centre for Scientific Research

Nadir observations of sprites from the International Space Station

E. Blanc,[1] T. Farges,[1] R. Roche,[1] D. Brebion,[2] T. Hua,[3] A. Labarthe,[4] and V. Melnikov[5]

Received 4 April 2003; revised 29 October 2003; accepted 4 December 2003; published 14 February 2004.

[1] The experiment LSO (Lightning and Sprite Observations) is dedicated to the optical study, from the International Space Station, of sprites occurring in the upper atmosphere above thunderstorms. The objectives were to study these phenomena and to validate a new measurement concept for future measurements of sprites from space at the nadir. The first measurements were performed in the frame of the flight of the French Astronaut Claudie Haigneré (mission Andromède) in October 2001. Observations were performed by two microcameras, one in the visible and near-infrared and the other equipped with a moderately wide band filter at 761 nm. This filter includes the most intense N_2 1P emission of the sprites and partly the oxygen absorption A band of the atmosphere. The light emissions from sprites occurring in the middle and upper atmosphere are then differentiated from the emissions from lightning, occurring more deeply in the atmosphere and then more absorbed. This paper presents the first observations of sprites from space at the nadir and statistics about the respective intensities of lightning and sprites emissions as observed with this experiment. *INDEX TERMS:* 3324 Meteorology and Atmospheric Dynamics: Lightning; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 0649 Electromagnetics: Optics; 7894 Space Plasma Physics: Instruments and techniques; 6969 Radio Science: Remote sensing; *KEYWORDS:* sprites, lightning, high-altitude discharges, sprite observations from space, spectral differentiation of sprite and lightning, atmosphere-ionosphere coupling

Citation: Blanc, E., T. Farges, R. Roche, D. Brebion, T. Hua, A. Labarthe, and V. Melnikov (2004), Nadir observations of sprites from the International Space Station, *J. Geophys. Res.*, *109*, A02306, doi:10.1029/2003JA009972.

1. Introduction

[2] Although sprites have long been observed over thunderstorms [*Vaughan and Vonnegut*, 1989], the first pictures were taken by chance from ground [*Franz et al.*, 1990] and from the space shuttle [*Boeck et al.*, 1995]. Dedicated experiments from aircrafts [*Sentman and Wescott*, 1993; *Sentman et al.*, 1995] and from the ground [*Lyons*, 1994; *Winckler et al.*, 1996] allowed their principal characteristics to be determined. Sprites are observed from ground at large distances from the thunderstorms near the horizon, where they are spatially differentiated from the lightning flashes. A review of the principal observations is given by *Rodger* [1999]. Sprites occur mainly after a positive cloud to ground lightning [*Lyons et al.*, 2000] but a few sprites have been associated with negative lightning discharges [*Barrington-Leigh et al.*, 1999; *Sao Sabbas et al.*, 2003]. Sprites can be laterally offset from their parent lightning by several kilometers to tens of kilometers [*Sao Sabbas et al.*, 2003]. Halos, occurring at altitudes of about 70 to 85 km, are associated with most of the sprites [*Wescott et al.*, 2001; *Miyasato et al.*, 2003]. By way of contrast, elves appear at altitudes of 85–105 km following intense lightning flashes [*Barrington-Leigh et al.*, 2001]. The first sprite observations in Europe [*Neubert et al.*, 2001] showed that sprites occur over moderate storms systems, weaker than the active thunderstorm systems producing sprites over U.S., suggesting that sprites may occur more frequently than has previously been supposed.

[3] Several source mechanisms for sprite production have been proposed. An electric breakdown by quasi-static fields [*Pasko et al.*, 1997] can explain the formation of halos [*Wescott et al.*, 2001], while electromagnetic pulses [*Rowland et al.*, 1996] can be the origin of elves [*Barrington-Leigh et al.*, 2001]. Sprites could be produced by relativ-istic runaway electrons triggered by cosmic radiation [*Roussel Dupré et al.*, 1998]. According to this last approach, the light emission associated with sprites is only a part of more complex phenomena implying a high-energy electron beam injected in the ionosphere with electromagnetic radio emissions in a very large frequency range associated with X-gamma emissions. The discovery of blue emissions produced by ionization columns in relation with sprites [*Suszcynsky et al.*, 1998] and of possible HF radar reflections on these columns [*Roussel Dupré and Blanc*, 1997] support this last approach, as well as observations of gamma emissions from the Earth's atmosphere by astronomy satellites [*Fishman et al.*, 1994]. However, other observations of sprites using high-speed cameras (1000 fps) show that the spatial structures of most sprites develop downward from the point of initiation at altitudes of about 75 km [*Moudry et al.*, 2002]. This effect

[1]Département Analyse Surveillance Environnement, Commissariat à l'Energie Atomique, Bruyères le Chatel, France.
[2]Département Conception et Réalisation des Expériences, Commissariat à l'Energie Atomique, Bruyères le Chatel, France.
[3]Laboratoire d'Astrophysique de Marseille, Marseille, France.
[4]Centre National d'Etudes Spatiales, Toulouse, France.
[5]Rocket Space Corporation ENERGIA, Korolev, Russia.

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seems not explained by the runaway electron theory. This could be produced by the short duration (1–3 ms) of the first step runway process. This also suggests the possibility that different kind of processes could occur in the sprite formation.

[4] Based on observations of the total optical energy emitted by a sprite, the total energy deposition in the upper atmosphere has initially estimated to be from 250 MJ to 1 GJ [*Heavner et al.*, 2000], but this figure has subsequently been revised downward by nearly two orders of magnitude, to 1–10 MJ [*Sentman et al.*, 2003]. All these observations and studies suggest a coupling between the atmosphere, the ionosphere and the magnetosphere, which was not suspected until now.

[5] Simultaneous measurements from space of the electromagnetic and particle emissions associated with sprites, however, need nadir observations, never performed until now. Luminous emissions from sprites have heretofore been observed from space at the horizon [*Boeck et al.*, 1995], which provide a side view of the events against the dark background sky, similar to nighttime ground observations. Measurements from the nadir are rather difficult because the light emissions of sprites are superimposed on the intense light emissions of the lightning diffused by clouds.

[6] We first propose in this paper a method of differentiation of sprites from lightning for space observations at the nadir, based on observations in a spectral range corresponding to an intense sprite emission band and close to an absorption band of the atmosphere. We then present the first observations of sprites, using this method, by the experiment LSO (Lightning and Sprite Observations) on board of the International Space Station (ISS). Finally, we present statistics of the respective intensities of sprites and lightning as observed with this experiment. The impact of these measurements is important for future observations of sprites and associated emissions from space.

2. Measurement Concept

[7] The method for the spectral differentiation of sprites from lightning is based on observations in a specific spectral band. This band is centered on the intense $N_2(B^3\Pi_g - A^3\Sigma_u^+)$ (3 – 1) emission line of sprites at 762.7 nm. The band includes a significant part of the O_2 ($b^1\Sigma_g^+ - X^3\Sigma_g^+$) (0 - 0) absorption band near 761.9 nm. The most intense emission band of the sprites appears in the synthetic optical spectrum of sprites due to electron impact excitation by lightning-induced electric fields, as presented in Figure 1a [*Milikh et al.*, 1998]. This band is weak in sprite spectra measured at the ground [*Hampton et al.*, 1996; *Morrill et al.*, 1998; *Wescott et al.*, 2001] (Figure 1b) because of the presence of significant O_2 column density along the slant path between the sprite and ground observing location. On the contrary, this emission will be observed from space because of weaker O_2 densities above the sprite. The light emissions from lightning within this band, produced deeper in the atmosphere, will be absorbed, as well as all man-made emissions from the ground surface. The signal to noise ratio of sprite measurements in this spectral band is then expected to be high. The method used to detect sprites in our observations is based on the narrow band filtered observations centered on 761 nm (Figure 2b). The width of the filter is about 10 nm, which includes the N_2 1P(9-8) 761.3 nm emissions in addition to the O_2 (0-0) and N_2 1P (3-1) emissions and includes most of the sprite emissions produced in this band.

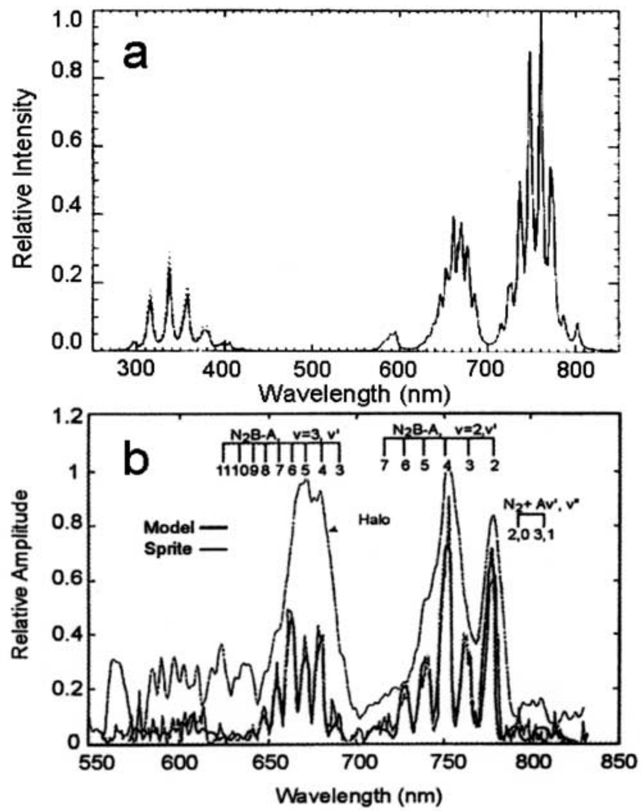

Figure 1. Sprite spectra. (a) Source spectrum [*Milikh et al.*, 1998]; (b) spectrum measured at ground [*Wescott et al.*, 2001]. A measured halo spectrum is also shown in this last figure with a synthetic sprite spectrum.

[8] The possible emission of lightning in the same spectral band is difficult to predict. The absorption of the atmosphere is not continuous in this frequency range. The spectrum measured by balloon [*Murcray*, 2001] shows that the transmittance is optimal below 759.5 nm, near zero between 759.5 and 761.8 nm, and is submitted to strong fluctuations between 761.8 and 766.3 nm. The expected intensity reduction factor is about 1.5 to 2 [*Fenn et al.*, 1985]. Such lightning emissions are rather difficult to observe at ground. An emission at 758.86 nm is reported in the list of the measured emission lines of lightning by *Uman* [1969], but the value as given in this list is uncertainly identified. The lightning spectrum measured above thunderstorms by aircraft by *Christian et al.* [1989] is probably too noisy to provide information in this band. A weak emission is visible in ground observations of *Orville and Henderson* [1984] at about 15 km from the lightning. A part of the lightning emission between 756 and 766 nm could then be transmitted by the filter which was optimized, in these experiments, for receiving the maximum possible emission from sprites and not for a complete elimination of a lightning effect.

3. Description of the Experiment

[9] The LSO experiment was proposed in the frame of the flight of the French astronaut Claudie Haigneré (mission

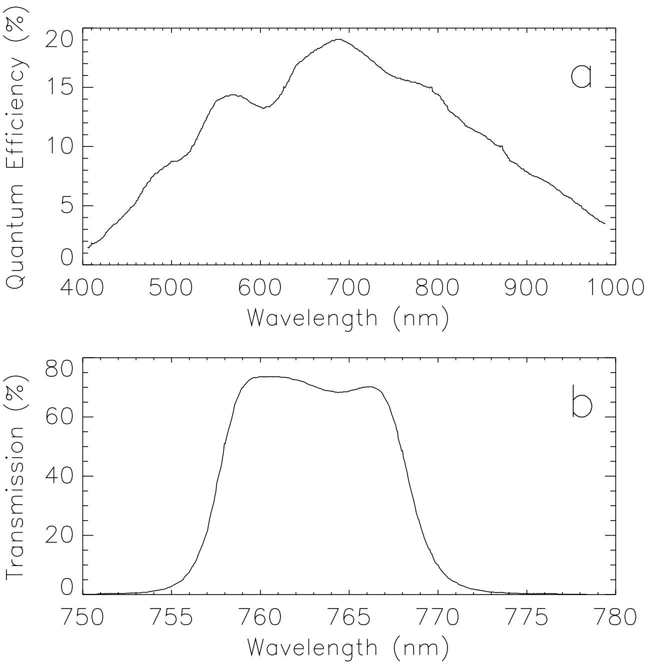

Figure 2. Spectral response of the LSO microcameras and of the filter.

Andromède) on the International Space Station in October 2001. The experiment was developed by the Commissariat à l'Energie Atomique with the participation of the Centre National d'Etudes Spatiales. The measurements were performed in collaboration with RSC Energia (Russia). The experiments, at first associated with the Andromède program, are now associated with missions of other European astronauts on ISS. The last measurements were obtained in the frame of the Belgium mission in November 2002. The results of this paper are based on the following LSO measurement periods: 14 to 17 October 2001, 26 April to 2 May 2002, 5 to 7 October 2002, and 8 to 9 November 2002.

[10] The experiment uses two digital space microcameras developed by CSEM (Centre Suisse d'Electronique et de Microelectronique), one equipped with a filter for the observations of sprites. The microcameras are not cooled. They use a 1024 $\times$ 1024 pixel ATMEL TH7888A CCD with 10 bits dynamic range. The pixel length is 14 μm with a pixel aperture ratio of 0.71 due to the antiblooming system. The objectives have a focal length of 14 mm, an aperture of f/3.5, and a field of view of 70°. The images of both cameras are taken simultaneously. The time of transmission of the digital images from the camera to the disk is large (4.5 s for 1 Mbytes). To lower this time, only the central part of the CCD (512 $\times$ 512 pixels) is used (the field of view really used is then 39.8°). The minimum possible exposure time is 1 ms, but measurements are performed with a higher exposure time of 1 s to increase the effective measurement period. The effective image frame rate is then 2 (for both cameras) per 5.5 s. The sprite bright emissions last a short time (a few ms up to 300 ms) compared to the exposure time of the cameras. They light the camera like a flash during the night. The time precision for the first experiments is few seconds. It is now improved to 1 s.

[11] The spectral response of the cameras and the filter are shown in Figure 2. The camera response is maximum at 690 nm, and the observation range extends from 400 to 1000 nm. The central wavelength of the filter is 763.0 nm with a bandwidth at 50% of 10.8 nm (757.6–768.4). The bandwidth at 1% is 19.5 nm. The filter transmission is 73.4%.

[12] Both cameras were calibrated for quantitative measurements of brightness. The flat field response of the camera was measured pixel per pixel to determine the lobe effect of the cameras. This calibration allows a correction of the pictures recorded by the experiment. A continuous source at wide spectrum and of measured radiance, coupled with a monochromator, was used for the measurement of the spectral response and of the sensitivity of the cameras. The spectral sensitivity of both cameras is nearly the same (the decay is lower than 4%) and is 45 $\mu J/m^2/sr$ at 765 nm for 1 LSB (least significant bit) or about 2 10^{-4} ft candles, which is comparable with the sensitivity of the camera used for the first sprite measurements from space [*Vaughan*, 1994].

[13] The cameras are fixed on a ISS window. The experiments are programmed by the astronaut (start and end time of the experiment, orbit parameters, type of experiment) at the beginning of the experiment; the measurements are then automatic. The two lines NORAD elements are used by an onboard program to compute the ISS orbit and to determine the measurement periods. Measurements are performed during nighttime. They can be programmed over continents were storms are mainly expected [*Christian et al.*, 2003]. Figure 3 indicates the measurement areas by different rectangles over continents. The oceans areas are represented by one rectangle in the Pacific Polynesian region. Typically, one experiment lasts 12, 24, or 36 hours. The surface of the ground observed by LSO during all experiments is shown in Figure 3. The color scale indicates the observation duration for each element of the observed surface. The average of this time is 8 s (that is, eight images).

4. Observations

[14] LSO observed 60 transient events with the camera in the visible. Figure 3 shows their location, and Figure 4 shows the distribution of their radiance. Most of these events do not appear in the filtered camera. This is also the case of most of the light emissions at the surface of the Earth produced by towns or man made activity and observed in several images successively with a position shift corresponding to the ISS motion. An automatic processing has been applied on all transitory events. It consists in suppressing the thermal offset of the cameras by subtracting the picture without event, taken just before the event picture, and in correcting the lobe effect of the objective using the flat field image.

[15] Among the 60 transient events, 13 were measured by both cameras. They are indicated by a number in Figure 3. They correspond to the most intense events observed in the visible. Table 1 presents their observation time, their intensity measured by both cameras, and the location of ISS at the time of observation.

[16] An example of bright transient event recorded by both cameras on 16 October 2001 at 1051:13 UT while

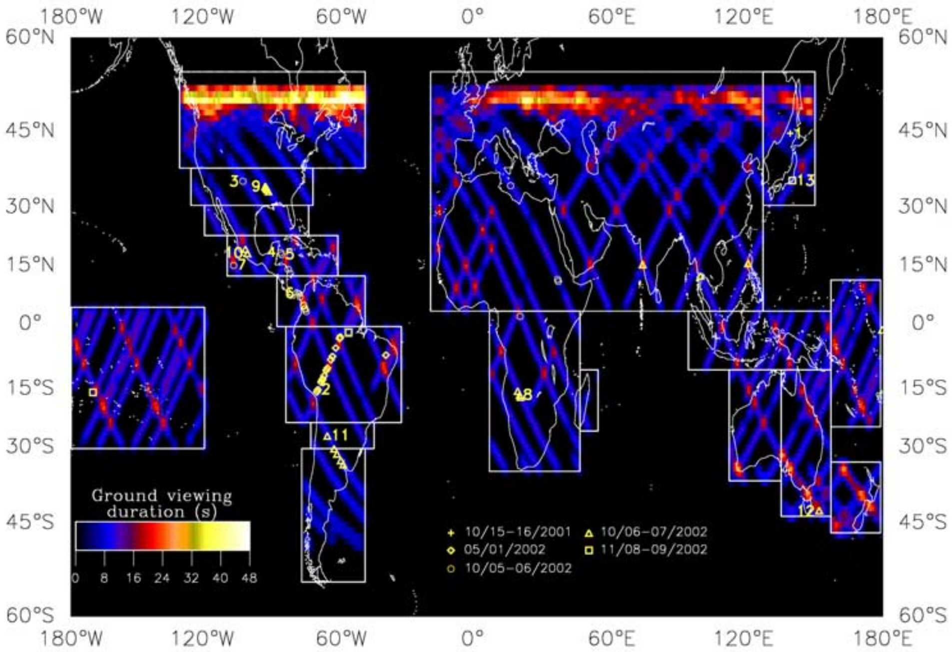

Figure 3. The LSO observation surfaces corresponding to the present observations are shown in color; the color scale indicates the integrated exposure time. All transitory events are positioned in the map. The events measured by both LSO cameras are noticed by a number and their characteristics are given in Table 1.

ISS was moving toward Japan is shown in Figure 5a. The intensity recorded by the camera in the visible (middle of the Figure) is about 800 LSB while the intensity measured by the filtered camera (top of the Figure) is about 15 LSB. The contour line underlines the common feature observed in both cameras. The event extends horizontally about 5 km. It is superimposed on a glow of lower intensity and extending over ~15 km. The ratio of the intensities received by both cameras is shown in the bottom of Figure 5a, this ratio (corrected for the filter transmission effect) is 2.7 to 5.5%.

[17] Figure 6 shows the lightning impacts at ground determined by the electromagnetic measurements of the Japan Lightning Detection Network in the time period of 2 hours centered at the event observation time. The color indicates the time. The storm was moving from 45°N–138°E to 47°N–142°E. The LSO image is shown in light gray. The event was observed in the upper left part of the image and appears in black. It has not been possible to determine exactly the lightning associated with the sprite because of a lack of time precision of the LSO data in the first measurement campaigns and because the average detection rate of the lightning network in the sprite area is about 85%, indicating that lightning flashes can be missed. At the event observation time, the event location coincides roughly with the lightning location.

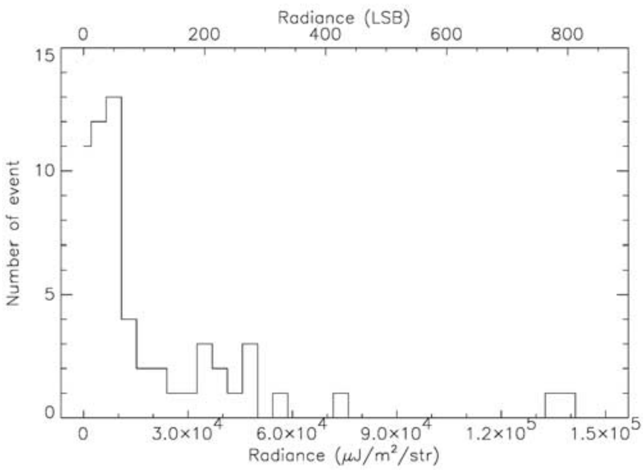

Figure 4. Distribution of the intensity of the events observed by LSO by the camera in the visible.

Table 1. Characteristics of All Transient Events Observed by Both Cameras[a]

	Date	Hour, UT	Maximal Intensity: Unfiltered Camera, LSB	Maximal Intensity: Filtered Camera, LSB	ISS: Longitude, °E	ISS: Latitude, °N
1	10/16/2001	1051:12	795.7	15.4	139.0	44.8
2	05/01/2002	0822:21	127.4	3.2	−69.9	−16.0
3	10/06/2002	0557:04	107.9	2.5	−103.0	35.3
4	10/06/2002	0602:58	280.0	6.0	−86.3	18.8
5	10/06/2002	0603:08	273.3	7.8	−85.9	18.3
6	10/06/2002	0606:23	276.1	3.1	−78.4	8.5
7	10/06/2002	0736:12	815.7	7.4	−107.2	15.7
8	10/07/2002	0041:03	329.3	4.8	19.3	−17.4
9	10/07/2002	0500:11	113.2	2.8	−93.1	34.2
10	10/07/2002	0637:55	286.9	5.5	−101.0	18.6
11	10/07/2002	0653:08	234.1	5.7	−65.7	−27.1
12	10/07/2002	1744:41	243.8	5.5	151.9	−42.9
13	11/08/2002	1652:58	435.4	10.9	140.0	35.4

[a]These events are indicated in the map of Figure 3.

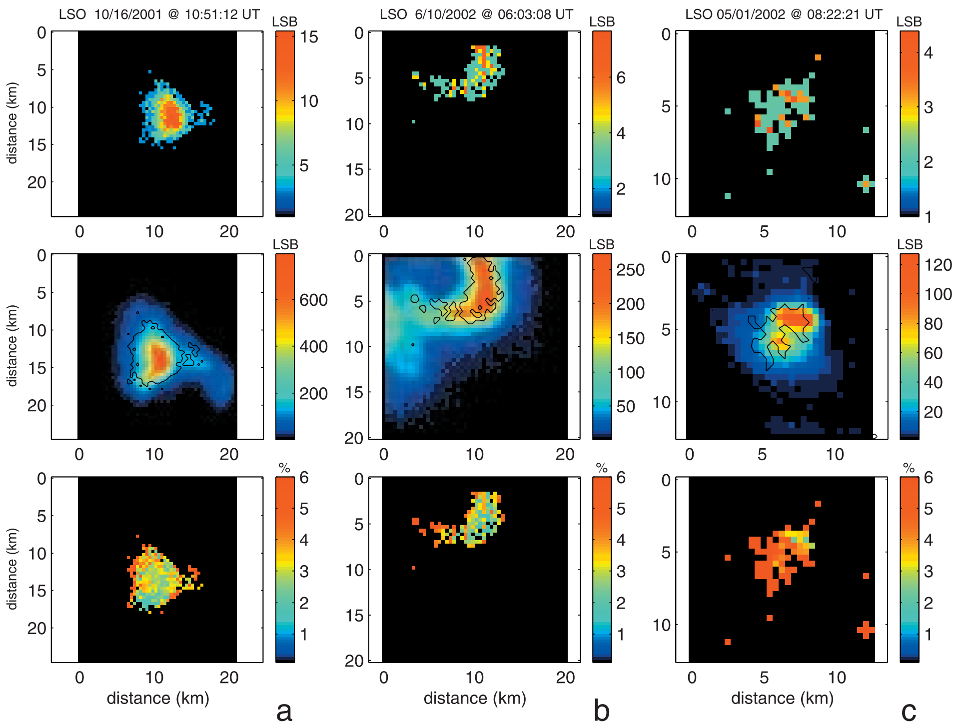

Figure 5. Examples of three events (a, b, and c) of the first class observed by LSO. The color scale indicates the measured intensity in LSB. (top) Filtered camera, (middle) camera in the visible and near IR, and (bottom) ratio of both camera intensities in percent.

[18] This example illustrates a first class of event defined by its ratio of both camera intensities higher than 3%. Ten events belonging to this class were identified. Two other examples are shown in Figures 5b and 5c.

[19] A second class of event is defined by a lower ratio of the camera intensities of about 1%. Only three events belong to this class. Two examples are shown in Figure 7.

5. Discussion

[20] The radiance of the LSO events, observed with the white light camera (Figure 4), has been compared with the radiance of previous lightning observations. The measurements performed by *Christian and Goodman* [1987] in a filter at OI(1) line at 777.4 nm from a high-altitude airplane showed that 90% of the lightning flashes produced energy densities higher than 4.7 $\mu J/m^2/sr$ with a maximum value of about 110 $\mu J/m^2/sr$. Assuming that this line contains 5–10% of all emitted energy in the visible and near IR spectrum, this would correspond to 67 to 1.5 10^3 $\mu J/m^2/sr$ in the LSO spectral observation range. The intensities measured by LSO are higher than the intensity observed by Christian and Goodman. However, Christian and Goodman recorded single short duration events while LSO integrates several of them within 1 s integration time. Differently, LSO intensities are comparable with the highest radiance values observed by the experiment LIS of the TRMM mission [*Christian et al.*, 2003], LIS considering flashes composed of several short duration lightning events. A study of the LIS detected lightning flashes has been performed using the LIS data available on the NASA Web site (2002). There were 25082 flashes observed by LIS during 147 hours of

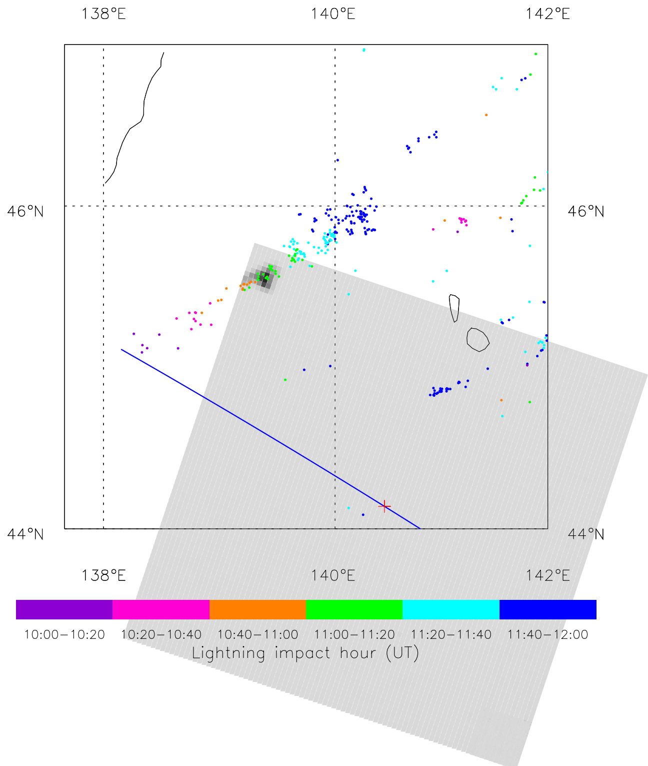

Figure 6. Lightning activity corresponding to the observation period of the event shown Figure 5a. The event appears in black in the left upper part of the LSO image (in gray). Lightning data were provided by the Japan Lightning Detection Network. The sprite was observed by LSO at 1051:13 UT on 16 October 2001.

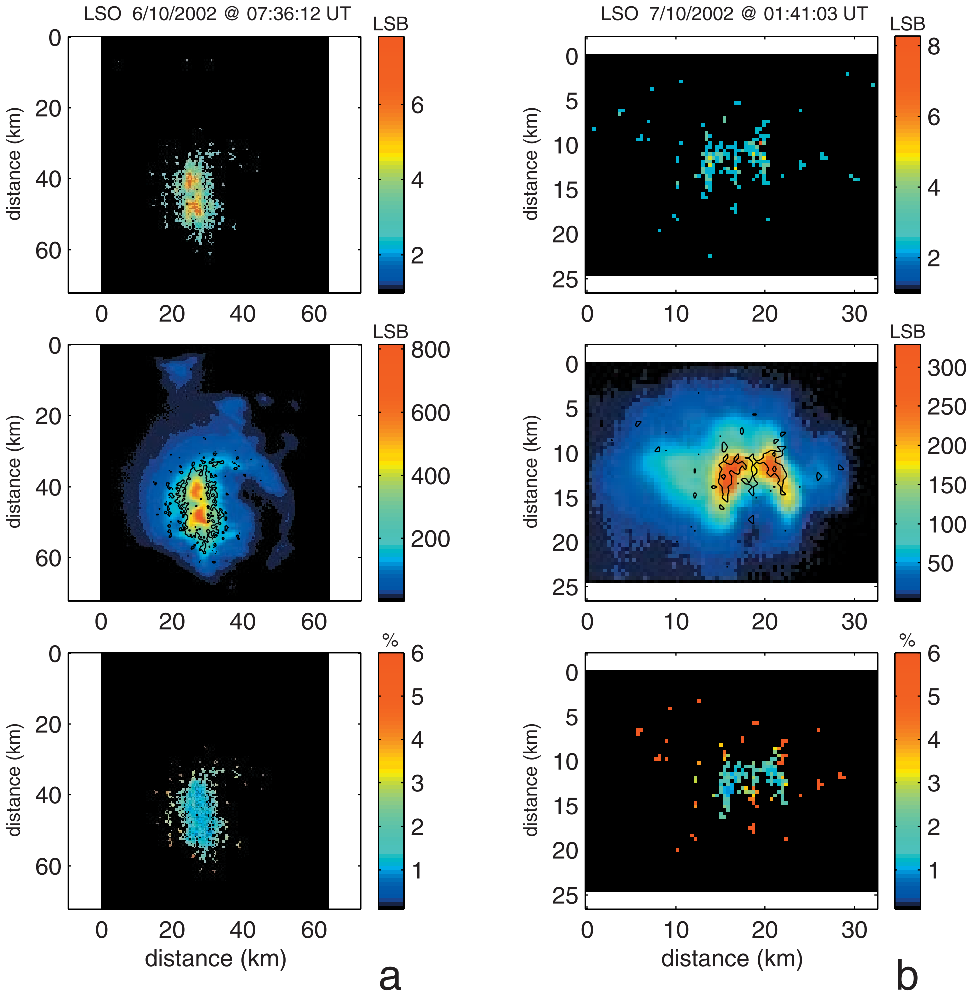

Figure 7. Examples of two events (a and b) of the second class. Same presentation as Figure 5.

measurements, corresponding to the LSO observation days. Taking into account the respective observation areas, the LSO effective measurement time and the fact that LSO measures only over the continents, where 88% of the lightning occurs [*Christian et al.*, 2003], it is found that the 60 transitory events observed by LSO correspond to about 25% of the LIS lightning flashes. According to this estimation, the total number of lightning flashes which would be observable in the 3.5 hours of LSO effective measurements is about 280.

[21] To compare also the LSO observations with other observations reported by *Turman* [1977] and *Kirkland et al.* [2001], we assume that the optical signal is produced by an isotropic light source and we estimate the peak power for the signal source by taking the product of the irradiance and $4\pi R^2$, where R is the measurement distance from the source. We suppose also that the lightning duration is 2 to 5 ms because several short duration lightning flashes generally occur in 1 s integration time. The power of the events, detected by both LSO cameras and determined by this way, is of the order of 5×10^{11} to 4×10^{12} W in the visible. This power is comparable with the power of the intense superbolts events observed by Turman and extending from 10^{11} to 10^{13} W.

[22] The 10 events of the first class observed by LSO are characterized by a higher ratio of the LSO camera intensities of about 2.7 to 5.5%. As the filter was designed to receive an important energy from sprites and to be less absorbed by the atmosphere than lightning, this class has been interpreted as a class of sprite events. The number of 10 sprites for 280 lightning is compatible with recent observations of sprites and lightning by *Sao Sabbas et al.* [2003], if we report their lightning and sprite observation areas in a same surface.

[23] A search for the possible parent lightning of the sprites observed by LSO on the visible camera has been performed. An example of possible parent lightning can be observed in the left part of Figure 5b in the camera in the visible. The distance from the sprite is about 10 km. This is in agreement with recent observations showing that parent lightning is not colocalized with sprites [*Wescott et al.*, 2001; *Sao Sabbas et al.*, 2003]. This lightning does not provide a clear response in the filtered camera. However, as several lightning flashes can occur during 1 s and as the lightning light can be diffused inside the cloud, lightning can contribute to the LSO intensities measured with both cameras. The 3–5% ratio of the intensities measured by both LSO cameras is lower than the ratio of about 10–14% directly deduced from the source spectrum. A contamination of about 20% by lightning emission in the filter response could explain this effect which can be reduced by a more selective filter.

[24] The three events of the second class observed by LSO are characterized by the lower ratio of the cameras intensities. They could be associated with superbolts. These very intense lightning flashes may produce a response in the filtered camera because the LSO present filter cannot completely suppress the lightning response.

[25] In the LSO 761 nm filtered observations, the measured radiance varies from about 1.2×10^2 to 10^3 μJ/m^2/sr. The sprite brightness is difficult to be evaluated because the sprite duration is not measured by LSO. It can be estimated roughly of about 10 to 100 MR assuming sprite duration of about 20 to 100 ms. These values are high but they are compatible with the brightness observed at the ground. *Stenbaek-Nielsen et al.* [2000] report that the sprite brightness, measured in the spectral range 500–900 nm with a rapid camera at 1000 fps, is "considerably higher than 3 MR" for most of the sprites. We expect to measure sprite brightness higher from space than from ground because the attenuation by the atmosphere is smaller from space at the nadir than from ground at the horizon (factor 2 to 3). In addition, the brightness for observations from the top will be more important than for observations from the side because of the sprite structure, larger vertically than horizontally (factor 1 to 50). LSO integration time is also longer than the integration time of sprite recent measurements at ground.

[26] The sprites observed by LSO are often associated with diffuse glows extending horizontally over 15 to 20 km (Figure 5). The 761 nm/visible intensity ratio of this glow received by both cameras is about 3 to 5%, comparable with the ratio obtained at the sprite peak, showing that these emissions occur at high altitude and are not associated with lightning. This glow often appears superimposed on the sprite, and it can be shifted by several kilometers as in Figure 5, where the sprite maximum location is not necessarily superposed with the halo maximum location. The event of Figure 5b is complex and compatible with the observation of a sprite, columniform sprites (appearing only on 1 to 3 pixels), and halo. The intensity of the halo is lower than the intensity of the sprite by a factor 2 to 5. The LSO measured halo extension is smaller than the halos extensions already observed at the horizon [*Wescott et al.*, 2001; *Moudry et al.*, 2003], but halos are varying spatially and are most intense in their center (LSO could miss the halo edge because of lack of sensitivity). Elves were not observed by LSO because they are more diffuse and less intense than halos [*Moudry et al.*, 2003].

6. Conclusion

[27] We have presented the first observations of sprites at the nadir from the International Space Station. The sprite identification has been performed by a spectral differentiation of sprites from lightning using an adapted filter at 761 nm, near the most important emission line of the molecular nitrogen and close to the oxygen A band absorption of the atmosphere. The differentiation is based on the use of two cameras, one observed in the visible and near IR and the second in the selected spectral band.

[28] The LSO experiment observed 60 transient optical events. Among them, 10 sprites were identified, all of which were very bright events with radiances in the 761 nm filtered camera of 1.2×10^2 to 10^3 μJ/m^2/sr corresponding to sprite emissions from 10 to 100 MR. These values are higher than the values which could be measured at ground at the horizon, because the atmospheric absorption is lower, and because the sprite geometry (larger vertically than horizontally) leads to higher intensities for top view than for side view observations. The sprite horizontal extensions varied from about 1 to 5 km. They are often associated with what appear to be sprite halos. Lightning does not produce a clear response in the LSO filter except for three events which could be interpreted as intense lightning; their power corresponds to the class of the superbolts.

[29] The measurement concept described in this paper will be used by the microsatellite Taranis (Tool for the Analysis of Radiation from Lightning and Sprites) dedicated to the study of sprites and associated phenomena and to the global analysis of the coupling between the atmosphere, the ionosphere and the magnetosphere in relation to these phenomena.

[30] **Acknowledgments.** The authors would like to thank C. Haigneré (F), V. Korzun (Ru), Y. Onufrienko (Ru), V. Dezhurov (Ru), and F. de Winne (B) for their participation in the measurements. They thank also J. J. Favier (CNES, F) and Y. Hobara (presently at the Swedish Institute of Space Physics).

[31] Arthur Richmond thanks the reviewers for their assistance in evaluating this paper.

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E. Blanc, T. Farges, and R. Roche, Département Analyse Surveillance Environnement, Commissariat à l'Energie Atomique, BP12, 91680 Bruyères le Chatel, France. (elisabeth.blanc@cea.fr; thomas.farges@cea.fr; roger.roche@cea.fr)

D. Brebion, Département Conception et Réalisation des Expériences, Commissariat à l'Energie Atomique, BP12, 91680 Bruyères le Chatel, France. (didier.brebion@cea.fr)

T. Hua, Laboratoire d'Astrophysique de Marseille, BP8, Allée Peiresc, Les trois Lucs, 13376 Marseille Cedex 12, France. (trung.hua@astrsp-mrs.fr)

A. Labarthe, Centre National d'Etudes Spatiales, 18 av. Edouard Belin, 31055 Toulouse, France. (alain.labarthe@cnes.fr)

V. Melnikov, Rocket Space Corporation ENERGIA, 141070, Lenin St., 4A, Korolev, Russia.