JOURNAL OF GEOPHYSICAL RESEARCH: SPACE PHYSICS, VOL. 118, 454–461, doi:10.1029/2012JA018144, 2013

Color pictures of sprites from non-dedicated observation on board the International Space Station

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Received 20 July 2012; revised 22 November 2012; accepted 28 November 2012; published 25 January 2013.

[1] Very recently NASA astronauts took a new set of pictures from the International Space Station during night time in the frame of the NASA Crew Earth Observations program, giving a new opportunity to observe in color sprites and their parent lightning flashes. During about 20 h of observations, nondirectly dedicated to thunderstorm studies, 15 sprites were observed from August 2011 to April 2012. Chromatic observations allow analyzing thoroughly the main components of the sprite radiation. The red and green emissions, observed in all the sprite images, are due to the radiation of the first positive band system of molecular nitrogen N_2. The blue emission, present in only 2 out of 15 sprites, is produced by the radiation of bands of the second positive band system of N_2 and bands of the first negative band system of N_2^+ ions. It indicates the possible presence of ionization in these two sprites. The sprite brightness is equivalent to the Jupiter one.

Citation: Jehl, A., T. Farges, and E. Blanc (2013), Color pictures of sprites from nondedicated observation on board the International Space Station, *J. Geophys. Res. Space Physics*, *118*, 454–461, doi:10.1029/2012JA018144.

1. Introduction

[2] In 1989, a new optical phenomenon called sprite was discovered over large thunderstorms [*Franz et al*., 1990]. Sprites are high-altitude discharges triggered by positive cloud-to-ground lightning discharges [*Lyons*, 1996], characterized by vertical extensions varying from ~40 to ~85 km and horizontal extension from few hundreds of meters to several tens of kilometers when they are grouped [*Wescott et al*., 2001]. They last only a few milliseconds [e.g., *Cummer et al*., 1998]. In 1994, dedicated experiments were organized to characterize them. The first color pictures were obtained by *Sentman et al*. [1995]. Sprites are mainly red in their upper part and blue in their lower part. This was the beginning of 20 years of intensive observations of Transient Luminous Events (TLE) [*Lyons*, 1996]. This hunt started in the USA and it is now organized all around the world and even from space [*Lyons*, 2006; *Pasko et al*., 2012]. The first space images of sprites were extracted from thunderstorm movies taken from the Space Shuttle in 1989–1991 [e.g., *Boeck et al*., 1998]. Several years after, the Lightning and Sprite Observations experiment was designed by our team [e.g., *Blanc et al*., 2004] and operated by European Space Agency astronauts from 2001 to 2004 on board the International Space Station (ISS). It was the first, and up to now, the only experiment observing sprites at nadir. In 2003, the Mediterranean Israeli Dust Experiment, on board the Space Shuttle, measured numerous sprites and elves from oblique and limb directions [e.g., *Yair et al*., 2003]. The ISUAL (Imager of Sprites and Upper Atmospheric Lightning) experiment, dedicated to TLE limb observations on board the low orbit satellite FORMOSAT-2, was launched in 2004 and was still working in 2012. This instrument gives a lot of information about TLE global distribution [*Chen et al*., 2008] and TLE radiometry in a very broad spectral range (from 160 nm to 780 nm in six broad or narrow bands) [e.g., *Kuo et al*., 2005]. All these space-borne experiments were equipped with monochrome video cameras.

[3] The NASA Crew Earth Observations (CEO) are ongoing since the early 1960s using different manned spacecrafts including the ISS, which is very well adapted to Earth observation. The main objective of the CEO is to photograph the Earth, the natural and man-made events. NASA astronauts took a huge amount of photographs, which are freely available from the Gateway to Astronaut Photography of Earth [CEO website].

[4] Our team at CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives) is involved in the development of an optical experiment for the future TARANIS (Tool for the Analysis of RAdiations from lightNIngs and Sprites) microsatellite developed by Centre National d'Etudes Spatiales, Toulouse, France, the French Space Agency, to detect TLEs and associated emissions above thunderstorm areas. TARANIS (Tool for the Analysis of RAdiations from lightNIngs and Sprites) payload includes a complementary set of instruments to analyze simultaneously energetic impulsive transfers associated to sprites, from radio wave to gamma ray including UV and visible as well as high energy electrons [e.g., *Blanc et al*., 2007]. Its launch is planned for 2015. New space-borne observations are then researched to improve the design of the cameras and then the future scientific feedback of TARANIS experiments. Similarly to *van der Velde et al*. [2007] and *Soula et al*. [2011], using nondedicated experiments to analyze gigantic jets, our team takes the opportunity to look for the sprite occurrence and characteristics by using CEO videos. The objective of this paper is to show color sprite pictures extracted from CEO experiments and to present a detailed

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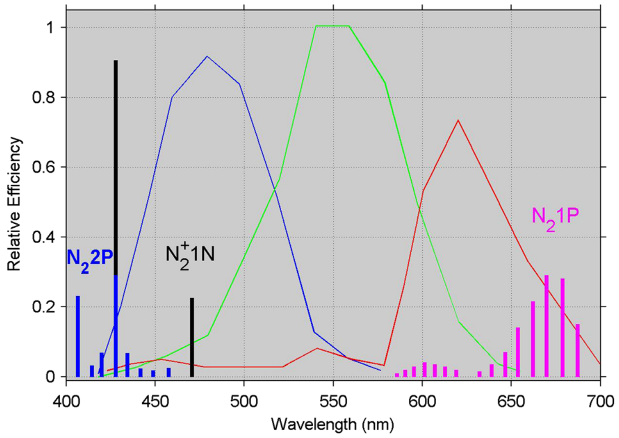

Figure 1. Nikon D3S camera response curves of the three color filters (blue, green, and red) compared to sprite radiation bands: (i) first positive band system of molecular nitrogen (N_2 (1P)) above 570 nm (magenta bars) (adapted from *Hampton et al*. [1996]), (ii) second positive band system of molecular nitrogen (N_2(2P)) below 470 nm (blue bars) (adapted from *Suszcynsky et al*. [1998]), (iii) two first negative bands of ionized molecular nitrogen N_2^+(1N) at 427.8 and 470.9 nm (black bars) (adapted from *Suszcynsky et al*. [1998]). N_2(2P) and N_2^+(1N) band intensities are relative between them but N_2(1P) band intensities are not comparable to these one.

analysis of the brightest sprite using the three color filters of the camera. To the knowledge of the authors, there is to date no published paper on sprite color observation taken from space.

2. New Observations From the ISS Cupola

[5] The most recent camera used by CEO is a Nikon D3S, which has a very high sensitivity, a high number of pixels (4276 × 2836 pixels), and a large memory. This color camera takes images through three partially superposed broadband filters: blue (420–540 nm), green (480–630 nm) and red (540–700 nm) (Figure 1). Lens, focal length and direction are chosen according to the CEO programs. This hand-held professional camera can be mounted for long sequence of observations (all along a half-orbit for instance). All ISS windows can be used including the cupola, which is docked to the ISS since 2010. The cupola window transmittance is high and constant in the visible spectrum (higher than 90%). Images taken about 1–3 s apart can be stitched together to form videos (available on the CEO website). which can run up to 40 min with short dead time between two consecutive frames.

[6] Many natural and artificial light sources are observed from the ISS during nighttime such as: stars, different ionospheric layers, auroras, meteors, lights coming from towns [*Zamorano Calvo et al*., 2011], and lightning flashes, when the ISS flies over thunderstorms. Samples of different observations are shown in Figure 2.

3. Several Color Images of Sprites

[7] One of the major advantages of these nondedicated nighttime observations is the new capability to survey all transient luminous phenomena including meteors, lightning flashes, and TLEs. From August 2011 to April 2012, almost 100 nighttime video sequences (that is about 20 h of observations) were examined frame by frame. Special attention was paid to tropical continent fly-bys because the lightning activity, and then the TLE activity, occurs mainly over this part of the world [*Chen et al*., 2008]. This examination revealed more than 50 meteors, thousands of lightning flashes, and 15 individual sprites. Videos usually correspond to different observation geometries in oblique direction toward the limb performed in a large field of view and an exposure time from 0.4 to 2 s. Distances extend from about 400 km (the ISS altitude varies from 330 to 410 km) to 2200 km (at the limb). The spatial resolution ranges from tens of meters at nadir to about 600 m at the limb. Such performances were never obtained up to now for a spaceborne instrument. However, at the limb, the resolution is not sufficient to identify individually each of the streamers composing one sprite.

[8] Fifteen sprites unambiguously observed by CEO are shown in Figure 3. Their observation conditions are listed in

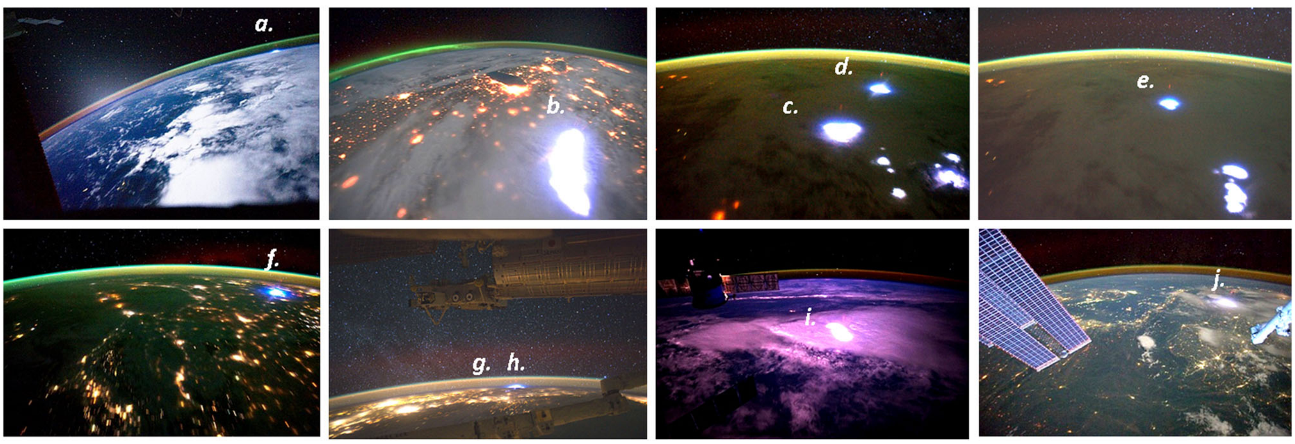

Figure 2. Pictures taken by CEO where sprites are obviously detected. The different point of views of CEO observations (oblique and toward the limb) clearly appear in the images as well as typical nighttime observations: stars, ionospheric layers, auroras, towns, lightning flashes, sprites (identified with a letter printed close to them), and the ISS itself.

Figure 3. Zoom of the different sprites of Figure 2.

Table 1. They appear as red glows, red filaments or a mixture of both. Their parent lightning flashes are white-blue and saturate the sensor. They are diffused by the atmosphere due to the Mie and Rayleigh scattering and appear as large glows. This is particularly obvious in Figures 3g and 3h when the observations are realized at the limb. However, this also appears in Figure 3b where sprite filaments are superimposed on a wide and diffused white-blue zone. Some sprites were photographed obliquely (Figures 3b, 3c, 3d, 3e, and 3i), and others at the limb. Sprites were not detected in the rare nadir observations, which nevertheless provide interesting lightning flash pictures with an unprecedented spatial resolution (~40 m) inside a large field of view of about 150 km × 100 km. Sprites were observed over the USA, the North Atlantic, Australia, the Solomon Islands, Caucasia, and Vietnam. The sprite location was retrieved using the ISS location at the picture time and the azimuth and declination of several stars observed simultaneously. An azimuth and declination grid was calculated by searching the best superposition of the observed stars and a sky map. This triangulation technique is similar to the one used by *van der Velde et al.* [2007]. Sprites c and d were observed in the same picture (Figure 2) within 2 s integration

Table 1. Information About Each Sprite Picture: CEO Image Name, the Date and Time (UT) of Observation, the Focal Length *f*, the Aperture Number *n*, the Exposure Time *t* in Seconds, and the ISS Location at the Observation Time (Latitude and Longitude in Degrees and Altitude in Kilometers)

	Image Name	Date	Time	*F* (mm)	*n*	*t*	Latitude	Longitude	Altitude
a	iss028e031144	20 August 2011	17:34:46	22	2.8	2	6.2°S	148.4°E	387
b	iss029e028787	18 October 2011	07:21:36	17	2.8	2	37.1°N	92.4°W	389
c	iss029e037312	29 October 2011	15:49:10	32	2.8	2	18.9°S	124.6°E	406
d	iss029e037312	29 October 2011	15:49:10	32	2.8	2	18.9°S	124.6°E	406
e	iss029e037318	29 October 2011	15:49:28	32	2.8	2	19.8°S	125.3°E	406
f	iss029e034192	29 October 2011	16:59:22	32	2.8	2	43.8°N	42.1°E	391
g	iss030e068922	23 January 2012	08:03:14	28	1.4	2	19.0°N	93.4°W	384
h	iss030e068942	23 January 2012	08:04:14	28	1.4	2	22.0°N	90.9°W	385
i	iss030e227588	12 April 2012	06:59:11	28	1.4	0.6	26.1°N	56.1°W	393
j	iss031e010712	30 April 2012	13:42:16	24	1.4	0.4	19.6°N	99.8°E	398

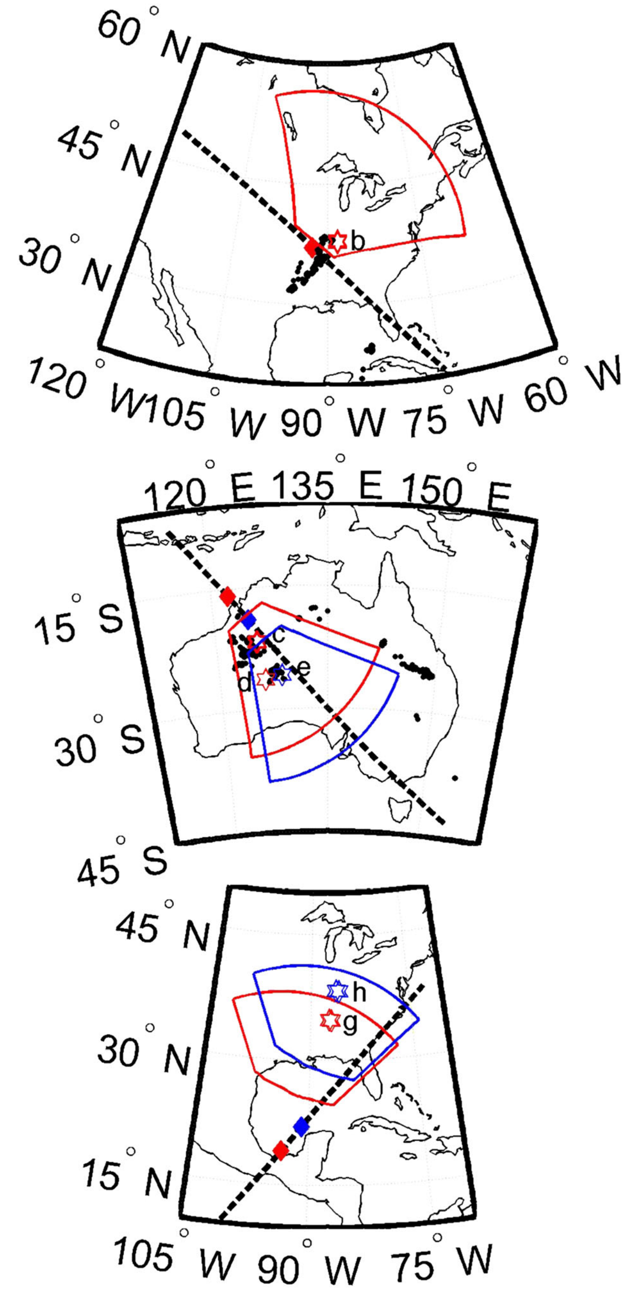

Figure 4. ISS location (red or blue diamonds) and trajectory (black dashed line), camera field of view projected on the Earth and detected sprite locations (red or blue stars): sprites b for the upper map; sprites c, d, and e for the middle map and sprites g and h for the bottom map. The black dots are the lightning flash locations measured 10 min apart the sprite detection by the WWLLN (for the bottom graph, 2012 data not yet available).

time, but they occurred about 500 km apart (Figure 4). Sprite e appeared 18 s after them but in the same region as sprite d. Similarly, sprites g and h were also observed on the same orbit 1 min apart over north of the USA. The three sprites b occurred over a very large lightning flash located close to St. Louis (Missouri). Many details can be seen thanks to the high proximity of the sprite from the ISS (only ~440 km). The i case was observed over the ocean where sprites quite rarely occur [*Chen et al.*, 2008]. The lightning data from the World Wide Lightning Location Network [e.g., *Hutchins et al.*, 2012, and references therein] showed that these sprites occurred over thunderstorm cells.

4. Sprite Spectroscopic Analysis

[9] The atmosphere and in particular its densest layer, the troposphere, strongly absorb light, and especially UV emission. Spectrometric observations of sprites can better be performed from space than from ground because, as sprites occur over the troposphere, radiation is less absorbed along the path toward an observer in space than toward an observer at ground. Full spectrometric studies from far UV to near infrared are then possible. A sprite photometric and spectroscopic study has been performed using CEO raw pictures. These raw pictures, which have a full dynamic range of 12 bits and are not modified by compression, are given by the CEO team under request. We focus our analysis on the brightest sprite observed at the limb (at the left of Figure 3h).

[10] Three images corresponding to the three color filters were extracted from the raw picture (Figure 5a). The sprite appears as a red glow including a bright narrow and vertical filament. It is superimposed on a horizontally continuous background extending from 50 to 120 km altitude in the ionosphere (scale on Figure 3h). This background emission corresponds to two emission zones: at 80–90 km altitude the OH (9–3) emission band (630 nm) and at 90–110 km the atomic oxygen band (557.7 nm). This radiation arises both in front of and behind the limb plan. From the ISS altitude, a diffused zone of several kilometers is observed (Figures 3f, 3g, or 3h) rather than a localized emission.

[11] The green and the red filter images show a large glow due to the sprite radiation, which extends from 57 to 74 km in the green filter and up to 84 km in the red one with a larger intensity (Figure 5a). Inside and at the middle of the sprite diffused light, one can see a vertical filament from 57 to 75 km, which is 1 pixel width (~600 m). In the blue filter, only this vertical filament is visible. *Stenbaek-Nielsen and McHarg* [2008] showed that the sprite streamer heads are spatially small (~100 m or less). The spatial resolution of the CEO images at the limb is not sufficient to enable the distinction between two streamers side by side as performed previously by *Gerken et al.* [2000] with telescopic imaging for example. The diffused zone below ~80 km is then due to several unresolved streamers. The strongest vertical filament could be due to a brighter streamer in the middle of the sprite.

[12] To have a more quantitative view of the sprite intensity, cross-sections of these three filtered images are plotted in continuous lines with the same amplitude scale at different altitudes (Figure 5b). The amplitude is corrected from the background radiation. The background vertical profile is calculated for the three images as the average of several columns free from sprites and stars. In Figure 5c, the blue (respectively green or red) curve represents the vertical profile all along the vertical filament discussed above. The sprite maximum width is less than 1 km in the blue image, 6 km at 69 km altitude in the green image and 9 km at 74 km altitude in the red image. The amplitude reaches its maximum for the

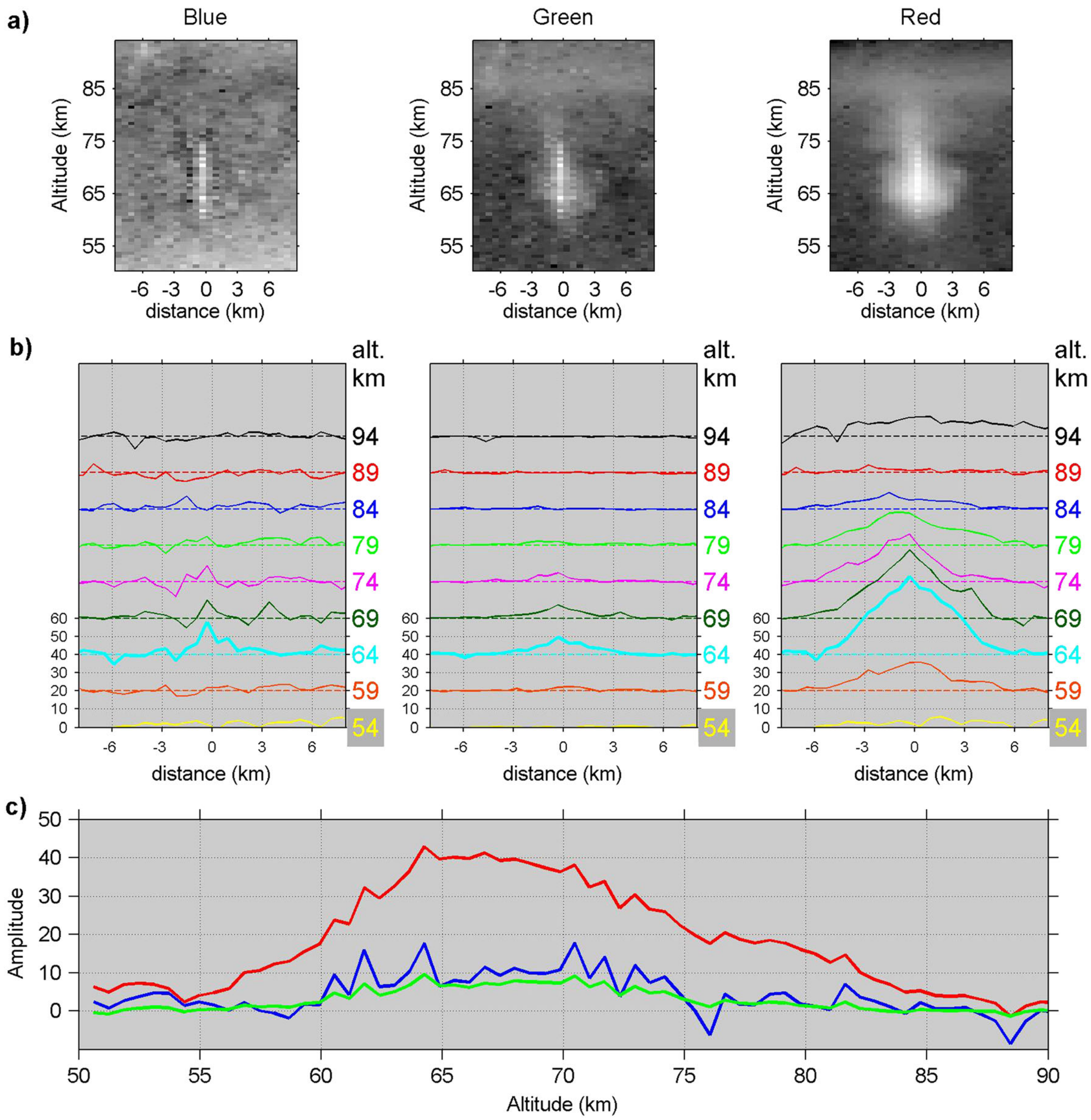

Figure 5. Quantitative analysis of the most intense sprite of Figure 3h. (a) Sprite images from the three color filters. Their spatial scales are deduced from simultaneous star observations. (b) Cross-sections intensity curves extracted at different altitudes with 5 km steps are represented for the same three images. For each altitude, their relative zero level is plotted as a dashed line at the same color. The amplitude is corrected from the background ionospheric emission. (c) Comparison of vertical profiles inside the vertical filament seen in the middle of the three images. The blue curve is for the blue filter image (and so on). The amplitude is also corrected from the background ionospheric emission.

three filters between 64 and 70 km altitude. In the red filter image the amplitude is about four times higher than in the blue or green filter (~40 in arbitrary unit for the red image and ~10 for blue and green images). The sprite vertical structure extends from 55 to 85 km in the red filter image and from 60 to 76 km in the blue and green images. The emission measured through the red filter is the brightest and the longest.

[13] Since the discovery of sprites, spectroscopic measurements and theoretical spectrum studies were performed to identify the origin of TLEs emissions and the energy involved to excite the atmosphere constituents. They show that sprite emissions are mainly due to the excitation of band system of molecular nitrogen: the first positive N_2(1P) bands from 550 to 4000 nm [*Mende et al.*, 1995; *Green et al.*, 1996; *Hampton et al.*, 1996; *Milikh et al.*, 1998; *Morrill et al.*, 1998; *Bucsela et al.*, 2003; *Kuo et al.*, 2005; *Kanmae et al.*, 2007; *Gordillo-Vazquez*, 2010; *Siefring et al.*, 2010; *Gordillo-Vázquez et al.*, 2011, 2012] and the second positive N_2(2P) bands from 300 to 450 nm [*Milikh et al.*, 1998; *Armstrong et al.*, 1998, 2000; *Suszcynsky et al.*, 1998; *Morrill et al.*, 1998, 2002; *Heavner et al.*, 2010; *Gordillo-Vazquez*, 2010; *Gordillo-Vázquez et al.*, 2011, 2012]. Other nitrogen band systems are at the origin of the UV emission: the Lyman-Birge-Hopfield bands and the Vegard-Kaplan bands

[e.g., *Gordillo-Vázquez et al.*, 2011]. Some studies are focused on the role of ionized molecular nitrogen: the first negative N_2^+(1N) bands from 388 to 475 nm and the Meinel N_2^+(M) bands from 550 to 900 nm. The Meinel bands were never clearly observed: several authors report the absence of such emission [*Mende et al.*, 1995; *Hampton et al.*, 1996; *Kanmae et al.*, 2007] while others suggest its presence but without a very obvious signature [*Green et al.*, 1996; *Morrill et al.*, 1998; *Bucsela et al.*, 2003]. This lack of detection could be due to the large amplitude of N_2(1P) bands, which can mask possible N_2(M) emission. Moreover, these bands are strongly quenched at high altitude (90 km) [*Piper et al.*, 1985]. The first attempts to detect ionization through the presence of the N_2^+(1N) bands from ground were inconclusive because N_2 (2P) and N_2^+(N) bands were measured together in a relatively broadband filter [*Armstrong et al.*, 1998; *Suszcynsky et al.*, 1998]. Using more accurate photometric measurements, *Armstrong et al.* [2000] showed that some sprites exhibit ionization, while others do not. *Heavner et al.* [2010] observed no ionization at 65 km altitude in one observation. Other measurements using a filtered imager showed that the ionization, when it occurs, is constant below 55 km while from 55 to 67 km altitude, simultaneous neutral N_2(2P) emissions increase with the altitude [*Morrill et al.*, 2002]. From space, with ISUAL narrowband (at 391.4 and 4.2 nm bandwidth) photometric measurements, *Kuo et al.* [2005] showed significant emissions from N_2^+(1N) in several sprites.

[14] Using the spectral response of the three filters of the D3S camera (Figure 1) and the previous spectroscopic studies, we analyze the present CEO observations (Figure 5). The light, in the red and green filter images, can be explained as due to the N_2(1P) bands because it requires less electron energy and it is the most intense emission in this spectral band as discussed above. The possible role of the Meinel bands is negligible. The amplitude of the emission through the red filter is more than four times higher than the green one because the N_2(1P) radiation is more attenuated by the green filter than by the red filter. We calculate the theoretical amplitude of N_2(1P) emission through the red and green filters taking into account the relative intensity of the N_2 (1P) bands and the filter transmission (Figure 1). We find a ratio between red and green signals of ~4.5, which is in very good agreement with observations. In detail, we found maximal amplitude of 42.9 in the red image and 9.6 in the green image, giving the 4.5 ratio. Red and green images are then complementary images of N_2(1P) radiation.

[15] To determine the origin of the blue image radiation and the possible presence of ionization, we use the relative band intensity of N_2(2P) and N_2^+(1N) given by *Suszcynsky et al.* [1998] and plotted in Figure 1. This suggests that most of the radiation measured in the blue image is due to the N_2^+(1N) band at 470.9 nm and that the blue image is mainly due to ionization. However, these relative intensities were obtained by laboratory experiments [*Davidson and O'Neil*, 1964] and are not fully relevant to sprite conditions but rather to electron beam conditions at high energy (50 keV). Differently, other measurements and spectrum calculations suggest that the N_2(2P) emission at 426.8 nm is the main contributor to the blue image. *Morrill et al.* [2002] calculated that the ratio between N_2(2P(0-0) – 337.0 nm) and N_2^+(1N(0,1) – 427.8 nm) ranges from 500 to 2500 mainly depending on the altitude. Considering the spontaneous emission probabilities [*Gilmore et al.*, 1992], the ratio of N_2^+(1N(0,1) – 427.8 nm) intensity over N_2^+(1N(0,2) – 470.9 nm) intensity is about 5. Furthermore, more recent work suggests that the ratio of N_2 (2P(0,0) – 337.0 nm) intensity over N_2(2P(1-5) – 426.8 nm) intensity is about 28 [*Gordillo-Vázquez et al.*, 2012]. We can then deduce from these ratios and the *Morrill et al.* [2002] measurements that the ratio between the N_2(2P(1-5) – 426.8 nm) intensity and the N_2^+(1N(0,2) – 470.9 nm) intensity should vary from ~90 to ~450. Taking into account the transmission response of the blue filter, this ratio becomes at least ~15. These computations show then that the N_2(2P) radiation can dominate the blue image.

[16] However, in our observations, the blue component has been observed only for 2 out of 15 observed sprites simultaneously with the red component, which always appears (including this one and the sprite in Figure 3j). This information is in agreement with the nonsystematic observation of ionization inside sprites as reviewed by *Armstrong et al.* [2000]. On the other hand, it is expected that all sprites have a blue counterpart due to N_2(2P) emissions, showing that in our observations the emission in the blue is not originating from the N_2(2P) emissions and that ionization is the main contributor of the blue image. This is probably not sufficient to thoroughly validate the ionization predominance over the blue image radiation but this is a strong indication of such effect.

5. Sprite Apparent Magnitude Evaluation

[17] The absolute brightness of the sprite shown in Figure 5 has been evaluated similarly as *Soula et al.* [2011], by comparing the sprite amplitude with the amplitude of a star observed at the same time (i.e., in the same picture) and which did not saturate the camera. The star HR7547, which is inside the Cygnus constellation, has been used as a reference for this calculation. This star is not contaminated by the ionospheric emission. Moreover, it is quite stable and there is no other bright star in its vicinity. The apparent magnitude of HR7547 is given for different spectral bands in Tycho2 catalogue [*Høg et al.*, 2000] and in the more recent Kepler catalogue [*Brown et al.*, 2011]. The most intense pixel of the sprite inside the vertical filament in the red filter has thus an apparent magnitude of +8.3. However, because sprite lasts few milliseconds while the star radiates continuously during the exposure time (2 s), its apparent magnitude is in reality +1.79 (for a 5 ms sprite duration). *Stenbaek-Nielsen and McHarg* [2008] found that a sprite streamer head can reach an apparent magnitude of –6. If we take into account a similar exposure time (50 μs, i.e., 20 times shorter than 1 ms), the maximum apparent magnitude thus becomes –3.2, i.e., an apparent magnitude close to the mean Venus or Jupiter brightness. The existing difference could be due to the spatial resolution of the two experiments (~600 m for this study and ~150 m for *Stenbaek-Nielsen and McHarg* [2008] study). The apparent magnitude gain induced by the surface ratio is about 4. The sprite apparent magnitude in present observations is then comparable to that of Stenbaek-Nielsen and McHarg observations. The sprite luminance can be deduced from the apparent magnitude (which is a brightness) taking into account the solid angle subtended by one pixel. For an apparent magnitude of +1.79 in the red filter, a luminance of about 12 MR is found. This is compatible with previous measurements

with an exposure time of a few milliseconds [*Stenbaek-Nielsen and McHarg*, 2008].

6. Conclusion

[18] The principal results presented in this paper can be summarized as follows:

[19] 1. Several NASA Crew Earth Observations were performed during night-time on board the International Space Station. A scrupulous analysis of these pictures allowed the detection of 15 sprites. These pictures have a high dynamic range and, to date, the best spatial resolution for space-borne observations. Moreover, they are color images

[20] 2. The color content analysis of the brightest of the observed sprite shows that the measured radiation is mainly due to N_2(1P) band system. Red and green images give complementary information about this radiation. The contributions to the blue emission are the N_2(2P(1-5)) band at 426.8 nm and the N_2^+(1N(0,2)) at 470.9 nm. The blue emission, present in only 2 out of 15 sprites, strongly suggests the presence of ionization in these two sprites.

[21] 3. The maximal absolute brightness of a sprite has been evaluated thanks to star brightness comparison. Its apparent magnitude can be compared to the Jupiter apparent magnitude. The sprite luminance is evaluated at about 12 MR.

[22] These new observations will be very useful for sprite studies, particularly to complement the future space missions dedicated to TLE observations at the nadir: TARANIS, ASIM (Atmosphere-Space Interactions Monitor) [*Neubert and ASIM Instrument Team*, 2009], and GLIMS (Global Lightning and SprIte MeasurementS) [*Ushio et al.*, 2011], and particularly the last two, which will fly on board the ISS. Future CEO nadir thunderstorm survey with high focal length and short exposure time would be a great complement for these future space-borne experiments. Because these images are available for anyone, amateurs can then also participate to the TLE hunt and help scientists to maximize the data science return.

[23] **Acknowledgments.** Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center. The authors wish to thank the astronauts who took the images from ISS, and S. Runco for her fruitful information about the CEO and the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, for providing the lightning location data used in this paper. The authors thank also both referees for their valuable remarks.

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