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Space observations of Transient Luminous Events and associated emissions in the upper atmosphere above thunderstorm areas

Observations spatiales des Évènements Lumineux Transitoires et des émissions associées dans l'atmosphère supérieure au-dessus des orages atmosphériques

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ABSTRACT

Sprites, jets and elves called Transient Luminous Events (TLE), observed in the middle and upper atmosphere above thunderstorms, are the manifestation of intense energy exchanges between the troposphere, stratosphere and mesosphere. Different types of luminous emissions have been identified by ground-based observations, showing the complexity of these phenomena. Space missions showed that transient emissions in the Earth atmosphere are very broad including Radio Frequency (RF), IR to FUV radiations and X-gamma ray emissions called Terrestrial Gamma Flashes (TGF) with energies reaching 30 Mev. However, there are no global observations of these events together. This paper reviews space observations performed up to now and emphasizes the challenges of the future space missions in global measurements of all possible emissions together for the understanding of the physical mechanisms at the origin of these phenomena and their effects on the Earth environment.

RÉSUMÉ

Les sylphes, jets et elfes appelés *Transient Luminous Events* (TLE), observés dans l'atmosphère supérieure au-dessus des orages atmosphériques, sont la manifestation d'intenses échanges d'énergie entre la troposphère, la stratosphère et la mésosphère. Les observations au sol ont mis en évidence de nombreux types d'émissions lumineuses démontrant la complexité de ces phénomènes. Les missions spatiales ont montré que les émissions transitoires dans l'atmosphère de la terre couvrent un spectre important incluant les fréquences radio (RF), l'infrarouge, l'ultraviolet lointain ainsi que les Flashs Gamma Terrestres (TGF) dont l'énergie atteint 30 MeV. Cependant, il n'y a pas d'observation globale de l'ensemble de ces phénomènes simultanément. Cet article passe en revue les observations spatiales effectuées jusqu'à présent et met l'accent sur les défis des futures missions spatiales qui consistent à mesurer, à une échelle globale, l'ensemble des émissions possibles nécessaires pour la compréhension des mécanismes physiques à l'origine de ces phénomènes et de leur effet sur l'environnement.

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1. Introduction

Sprites, jets and elves called Transient Luminous Events (TLEs), observed in the middle and upper atmosphere above thunderstorms (Fig. 1), are the manifestation of intense energy exchanges between the atmospheric layers. Brief optical emissions were already observed in the past by airplane pilots in the clear air above thunderstorms (Vaughan and Vonnegut, 1989), but the first image has been taken per chance at the horizon in 1989 during camera tests performed in the night for the preparation of a sounding rocket flight (Franz et al., 1990).

The first sprite observations from space were obtained during the Mesoscale Lightning Experiment in 1989–1991 from the space shuttle with sensitive low light monochrome video cameras during the night. The cameras were remotely controlled instead requesting active participation of astronauts. An analysis of hundreds of lightning storms near the limb provided 17 vertical flashes from cloud top toward the ionosphere (Boeck et al., 1995, 1998; Vaughan, 1994) confirming the presence of transient luminous events in the upper atmosphere above thunderstorm areas. Dedicated experiments on board of airplanes provided the first colour picture of a sprite and its dimensions from the top of the thunderstorm cloud up to the lower ionosphere (Sentman and Wescott, 1993). During dedicated observation campaigns, a large number of sprite images have been taken from the top of mountains at the horizon over mesoscale convective systems in USA (Lyons, 1994; Winckler, 1995) while other experiments in other countries showed that such events also occur over more moderate storms and are more frequent than expected (Neubert et al., 2001; Adachi et al., 2005). More than 10,000 ground-based images of TLEs were obtained in 2003 (Lyons et al., 2003). More than 400 TLEs have been observed above only one very active thunderstorm in Argentina (Thomas et al., 2007). Examples of sprite images are shown in Fig. 2 (Neubert et al., 2008).

Many different types of emissions were identified and differentiated as column and carrot sprites, trolls, jets, gigantics jets, halos, elves (Sentman and Wescott, 1993; Wescott et al., 1995; Lyons, 2006). The relevant scale lengths range from tens of meters to tens and hundreds of kilometres while the temporal scales range from hundreds of microseconds to hundreds of milliseconds. It has been shown that sprites and halos occur after an intense positive cloud-to-ground stroke generally identified using ground based lightning detection networks. Remote sensing using broadband ELF sensors at thousands of kilometres from the thunderstorms has shown that the minimum charge moment threshold required from the parent lightning to produce a sprite is in the range 350 to 600 Ckm (Cummer and Lyons, 2005). Differently, elves are observed after all lightning flashes that exceed a minimum peak current

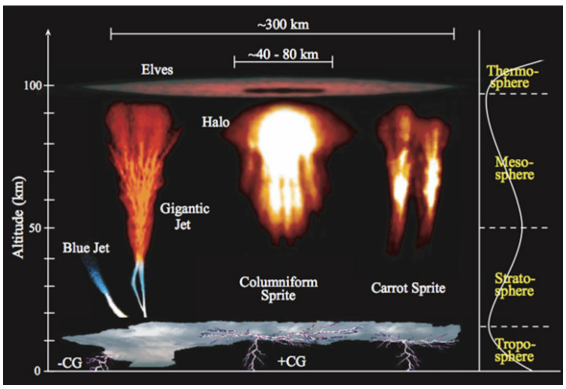

Fig. 1. Sprites, jets, elves, halos, gigantic jets in the Earth atmosphere (Sato et al., 2008).

Fig. 1. Sprites, jet, elfes, halos et jets géants dans l'atmosphère de la terre (Sato et al., 2008).

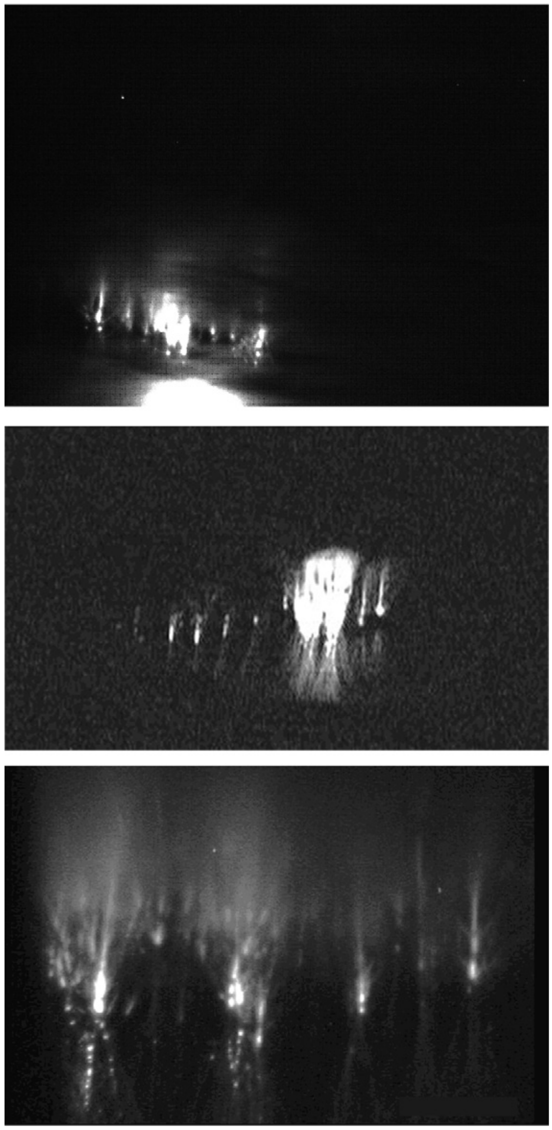

Fig. 2. Example of sprites recorded from *Pic du Midi* observatory during the Coupling of Atmospheric Layers (CAL) project (Neubert et al., 2008).

Fig. 2. Exemples d'images de sprites enregistrées depuis l'observatoire du Pic du Midi pendant le projet *Coupling of Atmospheric Layers* (Neubert et al., 2008).

threshold. They are produced by the lightning electromagnetic pulses and are then much more frequent than sprites (Barrington-Leigh and Inan, 1999). The electron densities generated in the mesosphere by sprites can reach $10^6\,cm^{-3}$ (Roussel-Dupré and Blanc, 1997) while the individual electron energies can range from a few eV to tens of MeV and produce emissions throughout the electromagnetic spectrum (Blanc et al., 2007a and references cited therein).

Large-scale effects induced in the atmosphere by sprite producing thunderstorms are gravity waves, which can be observed in the night airglow layer in the mesosphere (Sentman et al., 2003). Such gravity waves can be observed by satellites (Wu et al., 2006). They have a significant effect on the global circulation in the stratosphere and mesosphere with possible impact on climate (Blanc et al., 2009). At local scale, sprites produce infrasound characterized by a chirp signature (Farges et al., 2005). Possible local chemical effects (Arnone et al., 2008).

Recent developments show that fast (lower than 1 ms), high current ($>$ 100 kA) positive lightning induces diffuse airglow driven by conventional breakdown at the origin of TLEs at high altitudes ($>$ 60–70 km). Runaway breakdown triggered by cosmic radiation and at the origin of gamma emissions can then be initiated at the top of the cloud ($\sim$15 km) and develops upward to altitudes exceeding 90 km (Roussel-Dupré and Gurevich, 1996). For longer duration continuing currents (greater than a few ms), streamers driven by conventional breakdown develop at high altitudes ($\sim$75 km) and evolve downward to lower altitudes. The streamers can then be followed by a runaway discharge that is initiated at the top of the cloud and propagates to high altitudes (Roussel-Dupré and Gurevich, 1996; Roussel-Dupré et al., 2005). Other studies show that thermal electrons can be accelerated in the sprite streamers up to energies of several hundreds of KeV and possibly up to several tens of MeV producing runaway electron breakdown and gamma emissions in the upper atmosphere (Moss et al., 2006).

The images of sprites are dominated by red emissions produced by excitation of the $1PN_2$ band while blue emissions are associated with the $2PN_2$ and $1NN_2{}^+$ band that originates during the early development of sprites (Pasko, 2006; Pasko et al., 1997; Roussel Dupré et al., 1998). Measurement of $N_2{}^+$ emissions is critical to the evaluation of theories for sprite generation since the presence of such emissions confirms the existence of a sprite related ionization process in relation to run away avalanche processes. However, at ground it is only possible to observe the $1NN_2{}^+$ band in the blue, the other bands at lower wavelength being absorbed by the atmosphere (Armstrong et al., 1998; Suszcynsky et al., 1998).

Space observations are needed for measuring TLEs at global scale and all possible related emissions in the whole spectrum including UV, far UV (FUV), X and gamma emissions. Ground based TLE observations are described in review papers [e.g. (Lyons, 2006)]. The objective of this paper is to describe observations of TLEs and other possibly related emissions from space. The challenges of future missions are also discussed.

2. Space observations of Transient Luminous Events and other possibly associated emissions

All observations have shown the diversity and complexity of TLEs and associated emissions. Space observations are very important as they can give the whole emission spectrum and determine the global TLE distribution. They are also well adapted to measure associated gamma flashes in the earth atmosphere.

2.1. Transient Luminous Events

The first TLE space observations at the horizon were performed from the space shuttle in the beginning of the nineties (Boeck et al., 1992; Vaughan et al., 1992). Other observations especially dedicated to TLE measurements, were performed in January 2003 by the Mediterranean Israeli Dust Experiment (MEIDEX) conducted on board of the space shuttle Columbia during its last STS-107 mission. The mission lasted 16 days and was performed in a 39° inclination at an altitude of 280 km over-flight in the Atlantic and the Mediterranean Regions. The experiment used a Xybion radiometric camera model already used for ground-based observations. Shuttle attitude manoeuvres and camera orientation changes allowed optimal observations using forecasts of thunderstorm locations. The total number of observed TLEs (elves and sprites) is 17 within 254 min observing time (Yair et al., 2004; Israelcivh et al., 2004). Correlated ELF transients were detected for 5 of 7 elves at all ground stations with accurate geo-location of these events. However, none of the sprites were associated with ELF transients (Price et al., 2004). The lack of ELF signals for these events could indicate the presence of many more sprites than previously expected, caused by weaker, more frequent lightning flashes. Another unusual event observed by MEIDEX is the Transient Ionospheric Glow Emission in Red (TIGER) event, which could be originated from the conjugate point, implying magnetospheric processes (Yair et al., 2005).

Otherwise, in the years 2001 to 2004, the Lightning and Sprite Observations experiment (LSO), on board the International Space station ($\sim$400 km altitude, inclination 51.6°) proposed a new concept for nadir observations in a specific spectral band (Blanc et al., 2004). Such a concept opens the way towards future observations of all possible emissions simultaneously in space above thunderstorm areas.

TLE observations above thunderstorms are difficult because the light emissions of sprites are superimposed on the intense light emissions of the lightning diffused by clouds. It consists in observing TLEs in the spectral band centered on the intense N_2 ($B^3\Pi_g - A^3\Sigma_u^+$) (3–1) emission line of sprites at 762.7 nm. As this 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, lightning flashes will be absorbed in this band because they are produced below 15 km altitude where the density of dioxygen is high. On the contrary, TLEs, which occur above 30 km will be transmitted to ISS with small attenuation because of a weaker dioxygen density above the TLEs (Blanc et al., 2004, 2006).

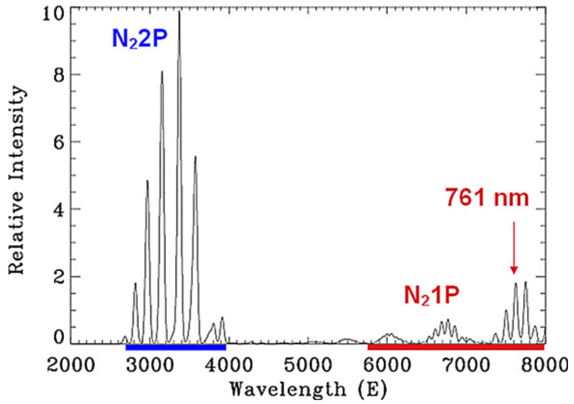

Fig. 3. Theoretical sprite spectrum (Triplett and Roussel-Dupré, 2005).

Fig. 3. Spectre théorique des sprites (Triplett et Roussel-Dupré, 2005).

These spectral bands are shown in the sprite spectrum of Fig. 3 (Triplett and Roussel-Dupré, 2005).

The LSO cameras sensitivity (∼2 mLux), was comparable to the sensitivity of cameras which took the first space observations of sprites (Vaughan, 1994). Both cameras were associated to an electronic box and an Experiment Processing Computer dedicated to on board programs and data archiving. Measurements were automatic. Data were archived on a removable disk, which was brought back to the ground by the astronaut. The first LSO measurements were performed in the frame of the Soyuz missions Andromède, Odissea, Cervantes and Delta.

LSO observed 180 transitory events with the camera in the visible and 40 events with both cameras during the 19 hours of effective measurements. Examples of TLEs and lightning observations observed at the nadir by LSO are shown in Fig. 4 (Blanc et al., 2007b).

TLE observations near horizon are now performed by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) on board the FORMOSAT-2 satellite, launched on May 2004 for 5 years of observations onto a Sun-synchronous orbit at 891 km altitude. The instrumental set includes an imager, a spectro-photometer using a set of multiple special light filters, and a photometer array for measurements at different altitudes in two different spectral ranges (Mende et al., 2006).

ISUAL observations have shown that TLEs mainly occur over areas where most of thunderstorms are observed (Christian et al., 2003), but with differences in the geographical distributions of the different types of TLEs: sprites are mainly observed above the continents, elves above the oceans, and halos over the coasts and the oceans.

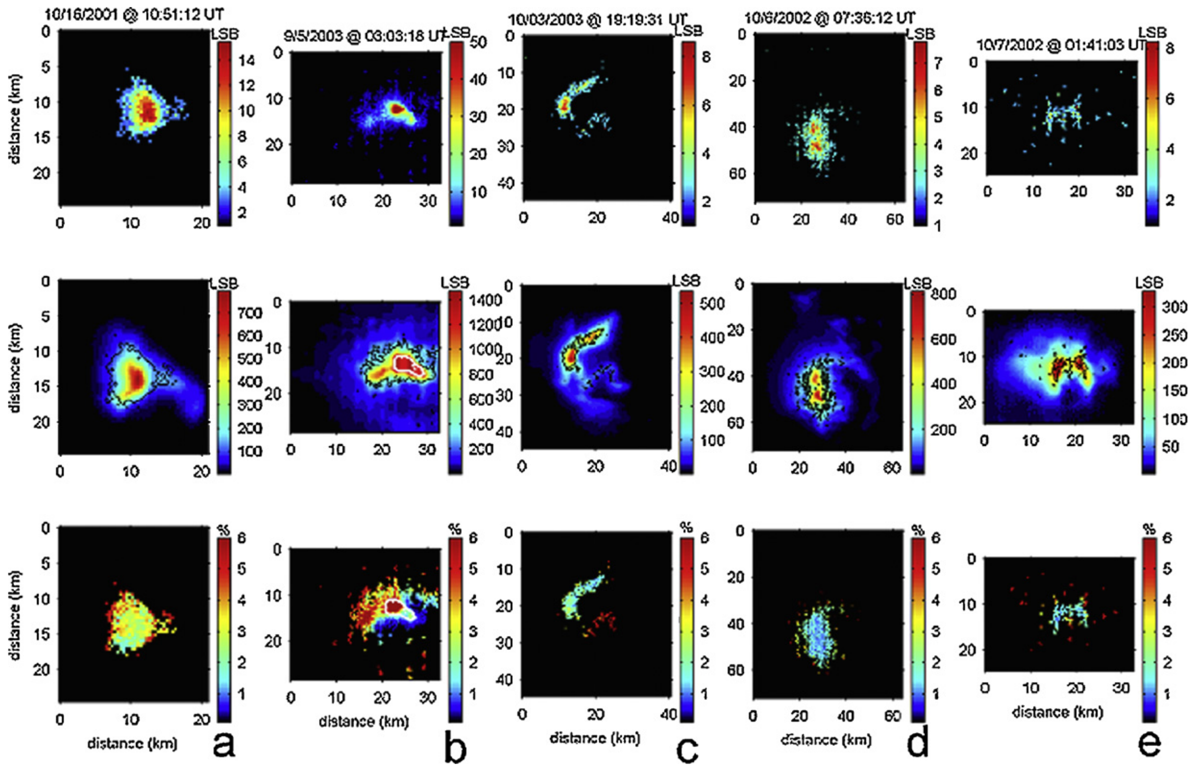

Fig. 4. Examples of LSO observations of possible sprites (columns a, b, c) and lightning flashes: (columns d, e). For each event, are shown: at the top, the image of the camera with the filter; in the middle the images of the camera in the visible; at the bottom, the ratio of both image intensities. Both events d and e with the lower ratio are very intense lightning while events a, b, c on the left with higher ratio and more complex response have been identified as sprites (Blanc et al., 2007b).

Fig. 4. Exemples d'observations possibles de sprites (colonnes a, b, c) et d'éclairs (colonnes d, e) par LSO. Pour chaque événement, le haut représente l'image de la caméra filtrée ; le milieu, l'image de la caméra non filtrée et en bas le rapport d'intensité lumineuse des deux caméras. Les événements d et e sont des éclairs intenses, tandis que les évènements a, b et c qui ont un rapport d'intensité plus élevé et qui sont plus complexes, ont été identifiés comme sprites (Blanc et al., 2007b).

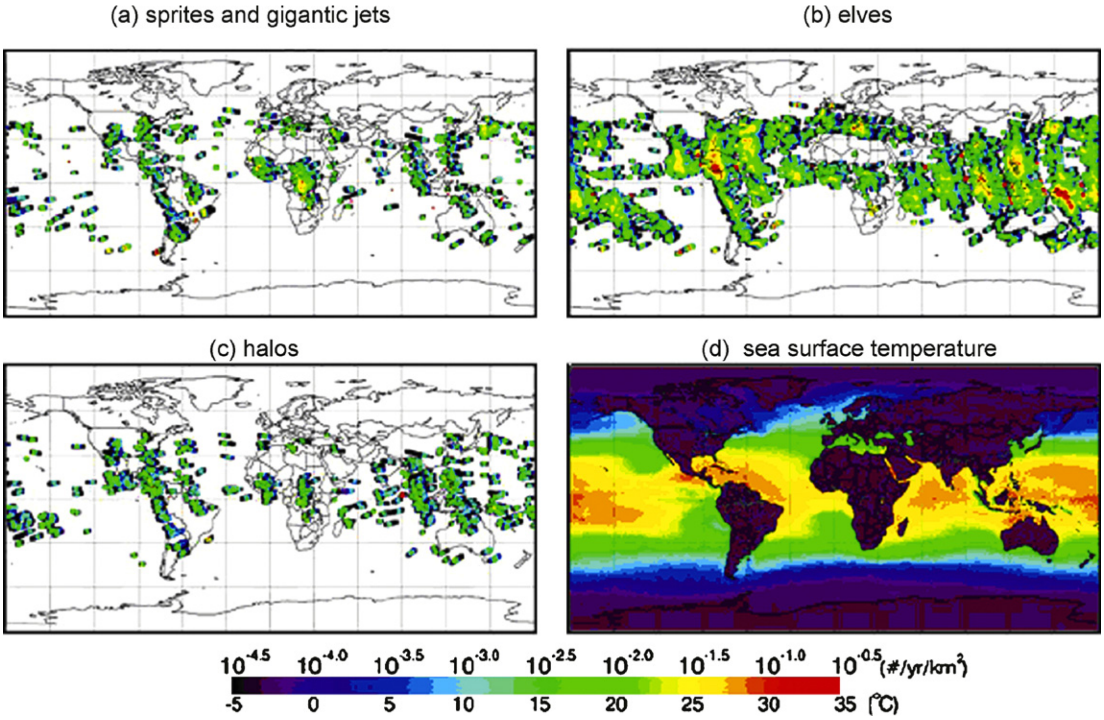

Fig. 5. Map of sprites, elves and halos measured by ISUAL and compared with the map of the sea surface temperature (Chen et al., 2008).

Fig. 5. Carte des sprites, elves et halos mesurés par ISUAL et comparés avec la carte de la température de surface des océans (Chen et al., 2008).

Elves are mainly observed over oceans when the sea surface temperature exceeds 26 degrees Celsius, manifesting an ocean-atmosphere-ionosphere coupling (Fig. 5 (Chen et al., 2008)). From July 2004 to June 2007, ISUAL recorded 5434 elves, 633 sprites, 657 halos, and 13 gigantic jets and the global occurence rates are 3.23, 0.50, 0.39, and 0.01 events per minute for elves, sprites, halos, and gigantic jets, respectively. Examples of TLE observations are shown in Fig. 6 (Kuo et al., 2005; Liu et al., 2009).

Measurements of the ratio of emissions in the blue and infrared bands provide the strength of the electric field. Sprites are initiated with streamers propagating in electric field reaching the local conventional breakdown threshold field. This is in agreement with the theory predicting that sprites are produced by conventional breakdown of air when the lightning field in the upper atmosphere exceeds the local breakdown threshold field (Liu et al., 2009). This mechanism explains diffuse light emissions in sprites produced without significant ionization process. At the sprite streamer altitude, the observed electric fields are larger and could imply other mechanisms and ionized processes (Adachi et al., 2006).

Significant emissions were observed by ISUAL in relation with sprites and elves in the N_2 Lyman–Birge–Hopfield (N_2 LBH) band of far UV due to the LBH band system (Fig. 6) (Frey et al., 2005; Mende et al., 2006). Models show that this band is stronger by a factor of 10 than those of the $1NN_2^+$ band (Liu and Pasko, 2005). Observations in this band are not contaminated by lightning, which is strongly absorbed by the atmosphere. This band will be used by future missions for TLE observations at the nadir above thunderstorms.

2.2. Terrestrial Gamma Flashes

Other emissions observed over thunderstorm areas are Terrestrial Gamma ray Flashes (TGF), observed per chance by satellites dedicated to gamma astrophysics.

TGFs were originally discovered by the BATSE instrument on board of the Compton Gamma Ray Observatory (CGRO) satellite (Fishman et al., 1994). During its nine-year lifetime in orbit, BATSE observed a total of 74 TGFs.

More detailed observations, including the energy spectrum, of TGF are now performed by the Reuven Ramaty High energy Solar Spectroscopic Imager (RHESSI) launched on February 5, 2002, which is a NASA spin-stabilized spacecraft in a low-altitude orbit inclined 38° to the Earth's equator. The only instrument on-board is an imaging spectrometer for colour movies of solar flares in X-rays and Gamma-rays. It uses two new complementary technologies: fine grids to modulate the solar radiation, and germanium detectors to measure the energy of each photon very precisely. RHESSI has observed to date some 10–20 TGFs per month (Smith et al., 2005a).

The geographical distribution of TGFs roughly corresponds to the geographical distribution of lightning over continents at low latitudes and also to the distribution of sprites (Chen et al., 2008; Christian et al., 2003). However, TGFs emissions are rarely detected over the Southern USA where many sprites are observed at ground (Lyons, 2006). The TGF distribution suggests that TGF are produced by lightning at the top of thunderstorm clouds because the high altitude of the tropical tropopause could allow TGF escape from the atmosphere (Williams et al., 2006).

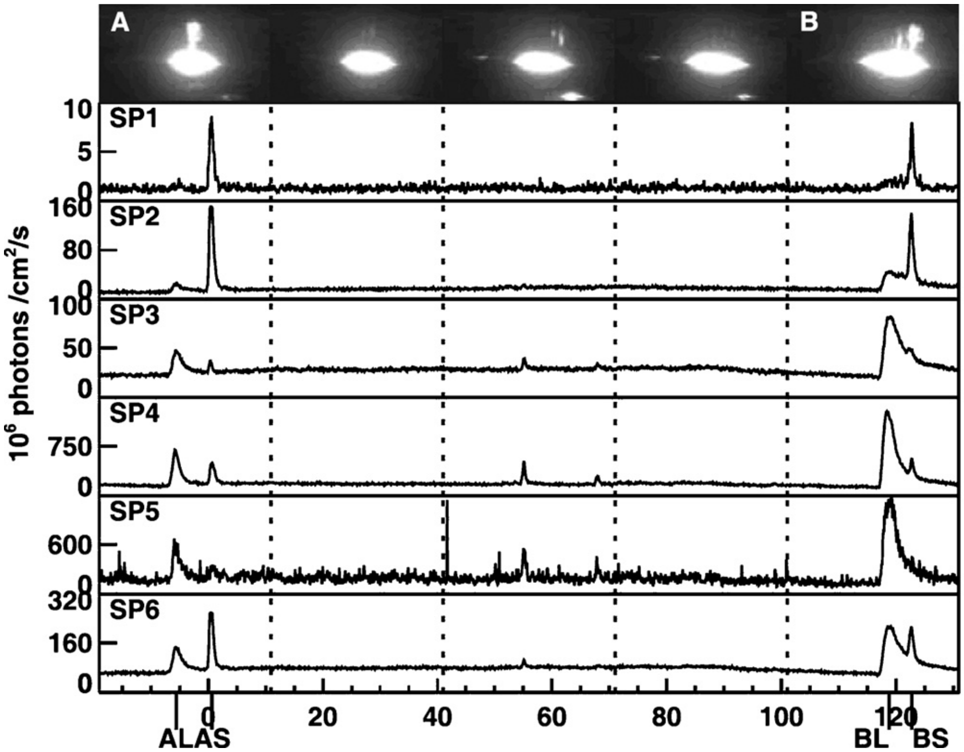

Fig. 6. Example of camera and photometer observations of sprites by the ISUAL experiment. Sprites are mainly observed at the times AS and BS while the parent lightnings are observed at AL and BL respectively. The SP1 spectral band corresponds to observations in FUV (Kuo et al., 2005).

Fig. 6. Exemple d'observations de sprites par caméra et photomètres par l'expérience ISUAL. Les sprites sont observés aux temps AS et BS, alors que les éclairs parents sont observés aux temps AL et BL respectivement. La bande spectrale SP1 correspond aux observations dans l'UV lointain (Kuo et al., 2005).

TGF spectra measured by RHESSI reveal energies up to 30 MeV (Smith et al., 2005a; Smith et al., 2005b), in agreement with energies predicted by the runaway relativistic electron breakdown mechanism triggered by cosmic rays (Roussel-Dupré and Gurevich, 1996; Roussel-Dupré et al., 2005). The low energy part of the TGF spectra is sensitive to the TGF emission altitude, due to the large attenuation of the low energy gamma rays in the atmosphere. The analysis of the RHESSI spectra suggests that the source is in the altitude range 15–21 km implying that thunderstorms and not sprites may be at the origin of TGFs (Dwyer and Smith, 2005).

Magnetospheric effects are suggested by (Dwyer et al., 2008) who showed that a substantial fraction of BATSE TGFs are, in fact, not gamma-rays but a new class of events composed of high energy electrons exiting the atmosphere and propagating back and forth along the geomagnetic field in the inner magnetosphere. A similar event has been identified in RHESSI data: the longer and most intense RHESSI TGF observed above Sahara desert in January, as thunderstorms are frequent at the conjugate point, has been explained as the manifestation of an electron beam hitting the spacecraft (Smith et al., 2005b). Magnetospheric effects of the electron beam associated to run away processes were predicted by theoretical studies (Lehtinen et al., 1999).

Observations at ground have shown that BATSE TGFs can be related with ELF/VLF signals exhibiting low tails as signals associated with sprites (Inan et al., 1996). However, RHESSI TGF parent lightning flashes are often characterized by weak charge moment changes. This suggests that the source is localized closer to the charge motion altitude, in or just above the thunderstorm and not at higher altitude (Cummer et al., 2005). Other studies show very large parent lightning peak currents implying large lightning electromagnetic pulses (Inan and Lehtinen, 2005). TGFs have been observed before or after lightning flashes (Cummer et al., 2005), which signify different source processes or a too low instrumental timing precision. In other cases, TGFs were observed without associated lightning (Inan et al., 1996; Cummer et al., 2005).

All those open questions about TGFs motivated a new recent analysis of BATSE spectra obtained previously. This shows that the source of most TGFs could be at altitudes between 10 and 20 km while others could originate from 30–60 km (Østgaard et al., 2008). However, a reanalysis gave lower altitude values in the range of 20 to 30 km (Østgaard et al., 2009). Such estimations are difficult because of the need of corrections in TGF signatures due to instrument dead time and electronic slowness effects.

TGFs were researched in other space missions also dedicated to gamma astrophysics. The AGILE Satellite, launched in April 2007, is an Italian mission devoted to high-energy gamma-ray observations in the 30 MeV–50 GeV range, with a window in the hard-X domain 18–

60 keV. One of the onboard detectors, the Mini-Calorimeter (MCAL), which was designed to detect transient events in the energy range 0.3–100 MeV detects about 9 TGFs per month (Fuschino et al., 2009).

The Gamma ray Burst Monitor (GBM) on the Fermi Gamma ray Space Telescope Observatory launched in June 2008 for cosmic gamma ray burst observations detects TGFs at energies up to ~40 MeV. Unlike the BATSE instrument, high counting rates can be recorded and deadtime characteristics are correctable, avoiding saturation effects. The number of detected TGFs is only about 1 TGF every 4 weeks (Fishman, 2009). This low number is due to the triggering system, which is not adapted to TGF observations.

2.3. Other possibly related transient emissions

Strong VHF electromagnetic pulses, called TIPPs (Trans Ionospheric Pulse Pairs) were observed by the experiment Blackbeard on board the satellite ALEXIS (Holden et al., 1995) and by the satellite FORTE (Jacobson et al., 1999). They are measured in the VHF range 20–300 MHz and composed of a first pulse followed by an echo from the ground and are the brightest known RF events. The altitude of the source deduced from the time difference between both pulses is at the top of the thunderstorms. TIPPs have been related to narrow positive bipolar pulses, which are isolated discharges, lasting a few to tens of microseconds producing radio emission in the range 1–30 MHz. Though not generally the case, a recent study has shown that such pulses can be correlated with TGFs (Stanley et al., 2006). Their source can be explained by runaway electron avalanches within electrified clouds, triggered by the background population of cosmic ray (Tierney et al., 2005).

Other studies show that extensive air showers (EAS) triggered by energetic cosmic rays can also seed runaway breakdown processes that produce narrow bipolar pulses and TGFs, but in this case light emissions are expected to be very weak (Gurevich et al., 2004; Gurevich and Zybin, 2005 May). Such emissions are then not related to TLEs.

More recently, the satellite DEMETER observed at 700 km altitude during nighttime HF emissions in a lower frequency range (1.7 to 3 MHz) at the time of powerful lightning below the satellite, within a few hundreds of kilometres from the satellite footprint. It was not possible to observe such pulses at low altitudes because of the high value of the critical frequency of the ionosphere, which prevents the propagation of the lightning pulses in the observation frequency range. It is suggested that a local ionospheric heating above thunderstorm areas favoured the propagation of HF heating up to the satellite (Parrot et al., 2008). Ligthning Induced Electron Precipitations (LEP) were also observed by the satellite DEMETER simultaneously with lightning VLF whistler waves (Inan et al., 2007). Such electron bursts are the signature of large regions of enhanced precipitations maintained by the lightning activity over thunderstorm areas. This suggests large magnetospheric effects related to thunderstorm activity (Lehtinen et al., 1999).

The Russian satellite TATIANA (~30 kg, polar orbit, 950 km altitude), launched in January 2005, is aimed at studying the processes and phenomena occurring in the Earth' magnetosphere (Sadovnichy et al., 2007). The payload is designed to study charged particles in the near-earth space and ultraviolet emissions of the atmosphere. The UV camera detects in the spectral range 300–400 nm, in low latitude regions, flashes, which could be produced by TLEs or TGFs. The map of UV flashes recorded during 2 years of observation is not correlated with continents as it is the case for lightning but is rather similar by some aspects to the TGF RHESSI map (Garipov et al., 2005). Such emissions could be produced by bunches of long streamers which form leaders of Gigantic Blue Jets (Shneider and Milikh, 2009).

3. Challenge for future space projects

To date, different observations show that the emissions above thunderstorms are very frequent and diverse and that mechanisms are complex. TIPPs/SIPPs, TGFs and TLEs have never been observed simultaneously, but the large electrostatic fields that develop in sprite/gamma ray/radio emissions production make for possible causality. While on the one hand many of the details regarding the optical characteristics of sprites and elves are presumed known, fundamental issues regarding the association of TLEs, TGFs, lightning, associated radio emissions and the nature of the source of penetrating radiation itself remain a mystery.

The first challenge for new projects is to understand physical mechanisms and this will be possible by measuring simultaneously all possible emissions together. The second challenge is to describe the global coverage and occurrence rates to evaluate the global impact on Earth environment.

Small microsatellites are dedicated to focused-objectives. The student microsatellite RISING (~40 kg), developed by Tohoku University in Japan is dedicated to measure either TLEs or TGFs at the nadir, the satellite resources being not sufficient for correlated observations. However radio wave observations could provide correlated measurements of lightning flashes. The scientific payload is composed of two cameras, a Gamma-ray detector and a VLF electric field receiver (Takahashi, 2009). The satellite has been launched on January 21, 2009. However, communication problems prevent the satellite activation after launching.

The Russian micro-satellite CHIBIS (~40 kg) and a second satellite RISING2 are developed to study the possibility of space monitoring for the detection and estimations of potentially dangerous and catastrophic phenomena on the Earth's surface, in the atmosphere, to the ionosphere and to the magnetosphere. The project proposes also to study the physical mechanisms at the origin of avalanching electrons in relation with TLEs and TGFs. The objectives are focused on TGFs and radio HF emissions in relation with extensive air showers (EAS) (Gurevich et al., 2004; Gurevich and Zybin, 2005 May) rather than on TLE observations. The payload (mass 12.5 kg) will include a X-gamma detector, a UV detector, a HF receiver (20–50 MHz), a camera and a magnetic-wave complex (0.1–40 kHz) (Klimov et al., 2009).

Table 1
Major science topics and questions addressed by the TARANIS mission.

Tableau 1
Principaux thèmes et questions scientifiques abordés par la mission TARANIS.

TLEs and TGFs observations	Locate geographical positions and altitudes of TLEs and TGFs source regions. Model variations with local time, season, activity indices, etc.
Environmental conditions	Identify parent lightning flashes and associated EM emissions Investigate possible correlations with cosmic rays, micrometeorites, volcanoes, etc.
Transfer of energy between the radiation belts, the ionosphere and the atmosphere	Detect and characterize bursts of precipitated electrons (LEPs) and of accelerated electrons (RBs)
TLEs and TGFs generation mechanisms	Provide input data (TLEs and TGFs source regions, association with lightning activities and other environmental parameters like EAS, bursts of precipitated and accelerated electrons) to test generation mechanisms
Contribution to the modelling of the effects on the atmosphere and on the global electric circuit	Provide information on sources of energy (TLEs, TGFs, bursts of precipitated and accelerated electrons) or/and on large scale ionospheric perturbations

TARANIS is a low-altitude CNES microsatellite project of the Myriade program (~150 kg, payload 32 kg) (Blanc et al., 2007a; Lefeuvre et al., 2006), dedicated to global observations of TLEs, TGFs, electric and magnetic emissions and high-energy electrons in the Earth atmosphere. The satellite will have a quasi sun synchronized polar orbit at 750 km altitude.

The scientific objectives of the TARANIS mission fall into three broad categories:

- Physical understanding of the TLEs, TGFs and of the links between them and environmental conditions (lightning activity, geomagnetic activity, atmosphere/ionosphere coupling, occurrence of Extensive Atmospheric Showers, etc.);
- Identification of other potential signatures of impulsive transfers of energy (electron beams, associated electromagnetic or/and electrostatic fields) to determine generation mechanisms;
- Providing inputs for modelling effects of TLEs, TGFs and bursts of precipitated and accelerated electrons (lightning induced electron precipitation, runaway electron beams) on the Earth's atmosphere.

Major Science topics and questions addressed by the TARANIS mission are given in Table 1 (Lefeuvre et al., 2006).

The satellite (Fig. 7) will yield a set of unprecedented and complementary measurements to study TLEs, TGF and associated emissions. The payload includes two micro cameras one for lightning observation (600–800 nm), the second for TLEs observations (762 nm), and four photometers in different spectral bands (762 nm, 337 nm, 150–280 nm, 600–800 nm) looking at the nadir, three X and gamma detectors (20 kev–10 Mev), two energetic electrons detectors (70 kev–4 Mev), four sensors dedicated to electromagnetic measurements using electric (DC–1 MHz and 100 kHz–30 MHz) and magnetic antennae (few Hz–20 kHz and 10 kHz–1 MHz).

The project Global Lightning and Sprite Measurement (GLISM), developed by Japan, proposes to observe TLEs

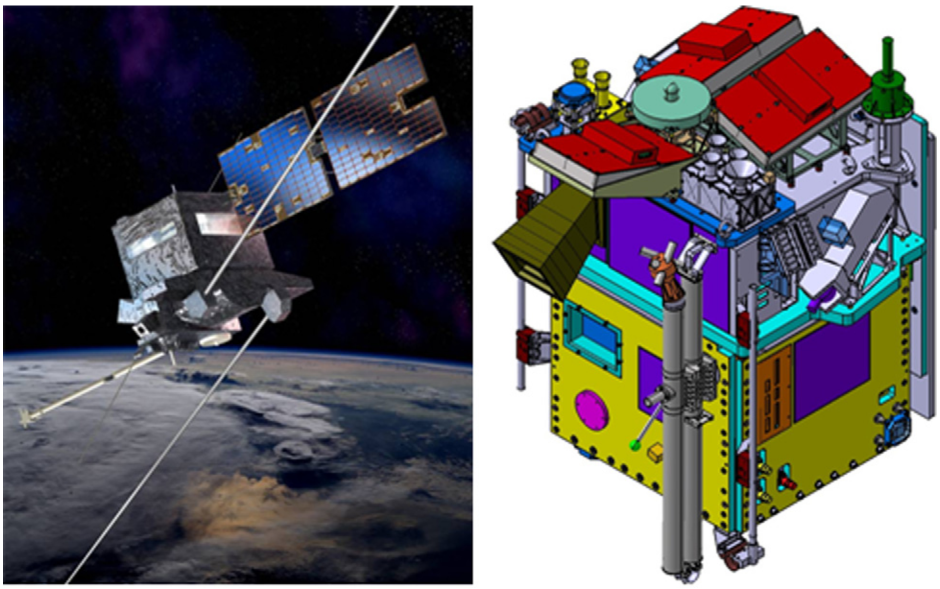

Fig. 7. TARANIS microsatellite: artist representation and satellite instrumentation details in the launching configuration.

Fig. 7. Le microsatellite TARANIS : représentation d'artiste et détails de l'instrumentation dans la configuration de lancement.

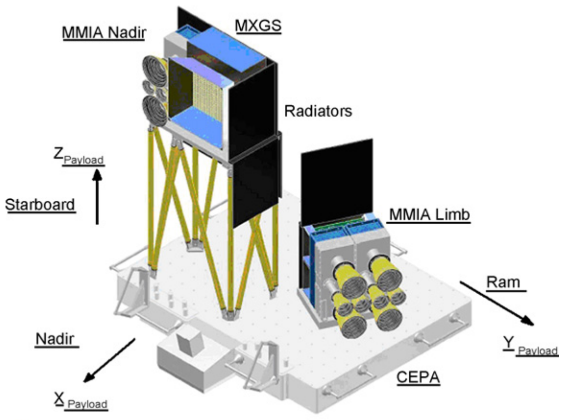

Fig. 8. The ASIM payload (Neubert and ASIM, 2008).

Fig. 8. La charge utile de ASIM (Neubert and ASIM, 2008).

from the Japanese module of the International Space Station at the nadir and to couple them with on-board VHF measurements. The payload is composed of two cameras (30 frames/s) similar to RISING cameras, 6 photometers identical to TARANIS photometers, a VLF receiver (DC to 40 kHz) similar to the RISING receiver and a HF interferometer (30 MHz–100 MHz). The instrument mass is about 26 kg (Sato et al., 2008).

The Atmosphere-Space Interactions Monitor (ASIM) (Neubert et al., 2006; Neubert et al., 2008) is an ESA project which will be mounted on the International Space Station on the Colombus module. It is dedicated to study thunderstorm effects on the stratosphere, mesosphere, ionosphere and magnetosphere.

The primary science objectives are to:

- Provide the most comprehensive survey to date of the occurrences of TLEs and TGFs on a global scale;
- Study the physics of TLEs and TGFs, their interrelationship and relationship with thunderstorm activity;
- Determine the characteristics that make thunderstorms TLE- and TGF-active;
- Study the coupling to the ionosphere of thunderstorms and TLEs.
- The research objectives that rely on modeling, using ASIM data as input, include to quantify:
- Chemical effects of TLEs and TGFs on the stratosphere, mesosphere, and lower thermosphere;
- Perturbations to atmospheric dynamics from TLEs and TGFs.

Additional objectives include to study:

- Water vapor transport to the upper troposphere and lower stratosphere by severe thunderstorms;
- Aerosols, and their effects on cloud formation and electric activity;
- Auroras during severe magnetic storms;
- Meteor ablation in the mesosphere and thermosphere.

ASIM is developed for the International Space Station in the framework of the Directorate for Human Spaceflight and Exploration of the European Space Agency. The ASIM payload is constituted by a very complete set for optical imaging (4 limb-cameras, 4 limb photometers, 2 nadir cameras and 2 nadir photometers), and a low-energy X- and Gamma-ray detector (Fig. 8).

4. Conclusion

Space missions are well adapted to measure TLEs above the thunderstorm clouds because they can provide their occurrence rates at a global scale and their signature in the whole spectrum including the absorption bands of the atmosphere. Such missions are also well adapted to measure TGFs, which are absorbed in the earth atmosphere. The satellite mission ISUAL, dedicated to TLE observations, provided the first maps of sprites, jets and elves and first signals in FUV. TGFs are only known through observations by satellites dedicated to gamma astronomy as RHESSI. Artifacts due to triggering or dead time, specified for other objectives, have to be taken into account in the data analysis and make data interpretation difficult. The interest for new observations is large and TGFs and UV flashes are presently researched in existing missions, which could have observed such events. However, there is a lack of observations of high-energy electrons, which can be associated to run away processes because previous and present missions were not adapted to the observations of transient events.

Our understanding of TLEs and TGFs still remains in many respects in a state of confusion and clearly points to the need for simultaneous high-speed measurements of electromagnetic waves across the entire spectrum and of associated high-energy electrons. Because of the directional properties of the energetic electrons and gamma radiation, simultaneous observations of TLEs, TGF and other possible emissions need to be performed from space directly above the active thunderstorm areas. This is the challenge of the new projects which all plan to perform correlated observations different kinds of emissions together. Among futures projects, ASIM on board of ISS proposes to measure a set of optical and X-gamma emissions in relation with climate, while TARANIS plans to also observe a large part of the electromagnetic spectrum and high energy electrons, adapted to a better understanding of ionospheric and magnetospheric processes.

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