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COBRAT PROJECT: LONG DURATION BALLOONS FOR THE STUDY OF HIGH ENERGY PHENOMENA AND CONSEQUENCE FOR STRATOSPHERIC CHEMISTRY

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ABSTRACT

The study of the Transient Luminous Events (TLE) and of the Terrestrial Gamma-ray Flashes (TGF) will be performed soon by the satellite instruments TARANIS (CNES) and ASIM (ESA, onboard the International Space Station). In complement to these measurements, observations are proposed to be conducted from long-duration balloons above equatorial regions. This project, called COBRAT, consists of gondolas with instruments dedicated to the detection of the TGF, TLE, electric and magnetic fields, and some atmospheric species that could be produced during these events. The various instruments are presented, as well as the proposed strategy of measurements from balloons and at ground.

1. INTRODUCTION

The discovery in the last decade of both Transient Luminous Events (TLEs) and Terrestrial Gamma-ray Flashes (TGFs) has revolutionized our understanding of the terrestrial environment by unveiling the frequent occurrence of impulsive transfers of energy between the troposphere and the space environment. Both phenomena are observed above thunderstorms and are supposed to be generated in the altitude range ~10-80 km. Fig. 1 present pictures of a sprite obtained with a fast-imaging camera. A rough estimate of the energy needed to produce standard TLE events over the continents (the sprite) provides a value of the order of 10 MJ [1]. TGFs spectra measured by the RHESSI satellite reveal energies up to 30 Mev [2]. These energy transfers can affect the chemical balance of ozone and nitric oxides in the upper atmosphere and can modify the global electric circuit.

Several space experiments have been designed to point out signatures of the generation mechanisms of TLEs and TGFs and potential consequences. Two of them, the ESA Atmosphere-Space Interactions Monitor (ASIM) and the Japanese Global Lightning and Sprite Measurements on JEM-EF (JEM-GLISM) will be embarked on-board the International Space Station. The third one is the CNES microsatellite mission TARANIS (Tool for the Analysis of RAdiations from lightNIngs and Sprites), which is the only one to have a comprehensive set of instrumentations. All three are in phase B and will be launched around 2013.

It is well known that high-energy phenomena can have implications to the stratospheric chemistry. In the case of high energy protons in the atmosphere coming from solar events, NOx enhancements have been reported from satellite observations at high latitudes [3]. Also, some enhancements of aerosols content in the stratosphere, detected from ground, seem to be correlated with such events [4]. In the case of TLE and TGF, the energy involved is lower and the events have a small horizontal extent. Then the enhancements, if they exist, may be smaller than those coming from solar protons. This is not in favour of detection by satellite instruments, which are not very sensitive to small-scale enhancements.

According to the altitude range of the generation mechanism and to the importance of the atmospheric effects, coordinated measurements are needed at ground (below the generation regions) and on balloons (in the vicinity of the generation regions). However, while the European Research Training Network "Coupling Atmospheric Layers" (CAL) (2002-2006) allowed fielding an impressive set of complementary ground-based stations [5,6], no coordination structure has been established so far for balloon-based measurements. It is the objective of the present report to propose the development of dedicated balloons and payloads.

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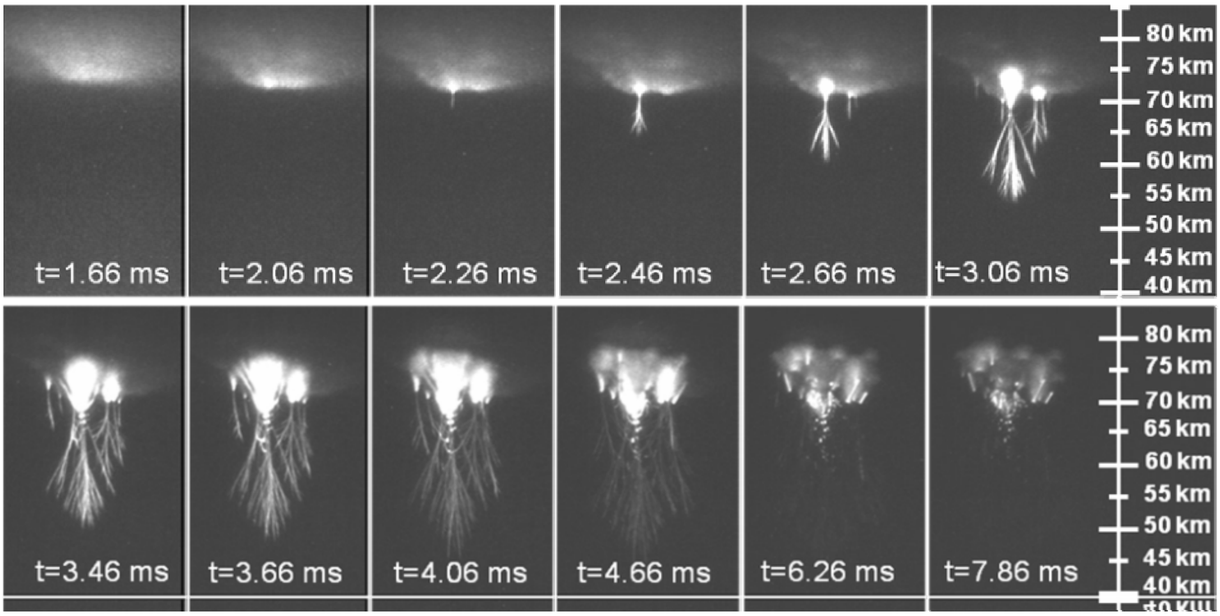

Figure 1. Pictures of a sprite obtained with a fast-imaging camera

As regards to the balloon, the main requirement is to have long durations flights (~10 days) at altitudes high enough (30 – 40 km) to make observations above potential source regions of runaway electrons and gamma rays and to potentially detect the NOx and aerosols enhancements. Although it is probably not the unique solution, the balloons which seem to be the best suited for the study of the generation mechanisms and of the effects on the atmosphere are long duration stratospheric balloons. The coupling of the atmosphere system with the ionosphere/magnetosphere system imposes multidisciplinary payloads with priorities which can be modified according to the spacecraft observations and to the geographical domains which are considered. In the following we will present the COBRAT (Coupled Observations from Balloon Related to Asim and Taranis) project: the long duration stratospheric balloons, the instrumentation dedicated to the physics of TLEs and TGFs, the stratospheric chemistry instruments, and the measurements strategy (including ground-based measurements).

2. LONG DURATION STRATOPSHERIC BALLOONS

At present, most of the instruments dedicated to the measurement of atmospheric parameters (ozone, NOx, and a tracer like N_2O or CH_4), to better determination of the origin of the air masses and their transport, are onboard Open Stratospheric Balloons, also called Zero pressure balloons. Such balloons can carry instruments weighting several tens to hundreds of kg and are launched for stratospheric flights typically lasting a few hours. As the generation time of TLEs and TGFs is not fully predictable (TLEs are rather observed at the end of lightning sequences, there is no clear indication for TGFs), it is difficult to know in advance the opportune launching time for a BSO. If, as a supplementary but very important constraint, one adds coordination with satellite observations, it becomes fully impossible. As a consequence, a new strategy of measurements is needed to fly above large convective systems and storms. It is based on flights of several days in the stratosphere. This would allow to cross several stormy structures per day and to strongly increase the probability to record several events at the time when the balloon and satellite measurements are coordinated.

MIR balloons (French acronym for Mongolfière Infra Rouge) can be flown in the stratosphere for tens of days. However, such balloons cannot carry more than a few tens of kg of instruments and above all, for reasons linked with radiation equilibrium, cannot be operated over large convective systems. So they are not well adapted for our scientific objectives. On the other hand, super-pressurized balloons can fly above the convective systems, but the actual mass-limitation, few tens ok kg, is a too drastic limitation for multi-instrumented gondolas.

The proposal which is made here consists in the development and the operation of new long duration balloons that can reside in the lower and middle stratosphere for more than one week. In fact, conventional BSO could be used for such purpose. Recent theoretical studies performed by CNES have shown that these balloons could stay several days in the middle stratosphere (altitudes in the 20-40 km range) and can carry heavy gondolas, typically up to 150 kg. The analysis were conducted assuming the use of 600 000 m^3 balloons and the release of ballast in order to minimize the decreasing altitude of the balloon due to its small but permanent loss of gas. Such balloons can fly over large storms and cloud expanses without any risk.

3. PHYSICS OF TLEs AND TGFs

At the present stage, there is no standard payload for the measurements of phenomena associated with the observation of TLE and TGF events. In what follows, we propose instruments that are based on experiences obtained in ground-based measurement campaigns and modelling.

The priority must be given to the on-board detection of TGFs and/or of electron beams accelerated from the bottom of the atmosphere to the ionosphere and probably to the Earth radiation belts. At 30 to 40 km altitude, one may expect to cross regions where energetic electrons are accelerated (or start to be accelerated) and gamma rays are emitted. At present it is proposed to use a simplified version of the TGF instrument that will be mounted onboard TARANIS. Because of the *in situ* observation from balloon, this instrument does not need to be as sensitive as the remote-sensing satellite instrument.

For detection of TLEs, priority is given to Blue Jets and Blue Starters which are difficult to observe from the ground. X-ray and optical instruments developed in the frame of the ASIM project are available at the Technical University of Denmark could be implanted in the gondolas. Independently, a system of cameras coupled with photometers is specifically developed for the balloon mission by the LATMOS team. The instrument will be used as an event trigger and will provide the information concerning the location and dynamics of stratospheric discharge and its relation with the tropospheric source.

Electric field measurements on board balloons will provide information one cannot get from ground-based and satellite-based instruments. This is the case for local electrostatic fields produced just above storms. At 30-40 km altitude they may be used to identify electrostatic structures of stormy cells. Observations have been made in the past using ground based "field mills" below thunderstorms [7]. For the stratospheric balloon measurements we propose a package of electric field instruments, which comprises "field mill" and short dipole antenna. Both instruments were developed in the frame of the NASA/ESA Martian Lander missions to study the dust particles, and were used for the stratospheric observations (HIBISCU, AMMA campaigns) above thunderstorm regions [8]. Large dynamic range (from few tens of $\mu V.m^{-1}$ to few hundred of $kV.m^{-1}$) and frequency range from DC to few kHz will allow to measure the electrostatic and electromagnetic perturbations generated by the electric discharges.

In particular, the measurement of electromagnetic wave field components in the ELF range ($f < 1$ kHz) of great interest. Short ELF emissions observed at ground are interpreted in terms of electromagnetic signatures of currents produced within sprites [9]. Such a signature, observed in ~ 20% of the cases, has not been pointed out on satellite so far. Measurements close to the sprite sources may help to better characterize these currents. VHF measurements are also a very interesting source of information. They identify the intracloud discharges ignored by the lightning detection systems [10].

For magnetic field measurement we propose to use the instrument developed in the frame of the TARANIS mission. This instrument is composed of 2 mono band antennas adapted to the 10Hz-20kHz frequency range, a double-band antenna adapted to the 10Hz-20kHz and 10kHz-1MHz frequency range, and 4 channels of measurement (3 ELF-VLF + 1 VLF-MF).

4. STRATOSPHERIC CHEMISTRY

Ozone and NO_2 measurements can be performed by remote sensing techniques, using Sun and the blue sky as light source during daytime, and Moon during nighttime. We propose to use the UV-visible spectroscopy to detect ozone and NO_2, as done at present, with SALOMON instrument [11,12]. Instead of using a pointing system, the observations will be conducted with a mirror mounted on a slow rotation system (typically around 2 degrees per second) that will scan the entire sky. When the Sun (or the Moon at night) is in the field of view, the integrated slant column of the species can be retrieved. When blue sky is observed, a vertical slice of the atmosphere is observed. By comparing the spectra recorded successively, relative variation of the integrated ozone and NO_2 content can be retrieved. Sensitivity tests show that column variations of less than $3.10^{14}cm^{-2}$ can be detected, which is at least 10 times below a moderate NO_2 enhancements produced by solar protons event. This new instrument is called ASPIC (Absorption SPectrometry Instrument for Cobrat).

Following the motion of the balloon carried by winds and the motion of the Sun and the Moon, a significant part of the stratosphere above the balloon altitude can be sampled by ASPIC. Nevertheless the altitude of the

NO_2 enhancements and their absolute value cannot be determined. Thus, another method of measurements is necessary to accurately detect the amplitude of the NOx enhancements. This can be conducted using an *in situ* technique such as the SPIRALE absorption spectrometer, using an onboard open cell and infra red tuneable laser diodes [13,14]. A lighter version of SPIRALE, called SPIRIT (Spectromètre InfraRouge In siTu), more accurate and easier to operate, is now available at ground [15], benefiting from the last advancements of optical technology. It consists of a new type of multiple-reflection optical cell [16], in which tuneable Quantum Cascade Lasers beams operating at room temperature undergo absorption on their path length by the trace gases to be quantified. This new spectrometer SPIRIT can be adapted to be implanted onboard a long duration BSO, and to perform measurements of ozone, NOx and one or two tracers (like N_2O, CH_4, CO, …) that can be chosen in advance. In this case, the altitude and the amplitude of the NOx enhancements can be accurately documented, but the probability of detection is smaller than with remote sensing techniques. Then the two techniques of measurements (remote and *in situ*) appear to be complementary.

The possible production of aerosols during high energy phenomena is highly speculative, so it seems difficult to allow a large amount of mass, energy and cost to such detection. Fortunately, a new light (around 1 kg) and not expensive aerosols counter is under development and will be available in 2010. This instrument will use a new method of observation to detect the aerosols in the 0.3-20 µm range whatever their nature (which is not the case for aerosol counters used at present that are not sensitive to black and absorbing solid particles). Also, this instrument could indicate the main nature of the aerosols (liquid, solid, soot, plasma dust, ...). Thus, we propose to put inside the gondolas such an instrument to confirm the presence of local enhancements of aerosols linked to TLEs and/or TGF, and to tentatively determine their nature.

5. STRATEGY OF MEASUREMENTS

Because there is no standard payload, several scenarios may be envisaged. The different instruments can be put on the same gondola. In that case, the main limitation will be the weight of all the instruments together. The best scenario probably consists in the implementation on the same gondola of the instrumentation for the physics of TLEs (cameras, electric fields). For the ensemble of optical, electric field and magnetic field observations we propose the gondola based on principles developed in LATMOS and tested during previous stratospheric (Fig. 2) and ground-based experiences. The main characteristics of this gondola are the weak power consumption, weak weight, on-board data processing and data saving. New generation of this gondola type based on new technologies, including the satellite TM, is planned to be developed in the next few years. Another gondola will be dedicated to the instrumentation for TGFs and the instruments for stratospheric chemistry.

Another important point to examine carefully with CNES is the electric power needed for the instrument and the data transmission capacity. Even if the use of satellite links is possible, it is possible that the telemetry capacity may affect the payload. Trade offs could be necessary.

Figure 2. The LATMOS gondolas for TLE and electric fields measurements

As regards to the observation regions, other trade-offs are required. If satellite observations of TLEs [17] and TGFs [2] are made over thunderstorms areas, all thunderstorm regions do not produce TLEs or/and TGFs. Assuming that the priority for the balloon-based measurements are the observation of TGFs, one must launch close to the equator either above America, Africa, Indonesia or North Australia. Also, the TGF measurements cannot be performed close to the South Atlantic Anomaly. To this regard, the available launching bases used at present (Aire sur l'Adour, France, Kiruna, Sweden, and Teresina, Brasil) are not suitable. New sites must be searched for, for example Kourou (Guyana) or Northern Australia. The launch conditions at ground and the cost of the campaign will give strong constraints for the choice of the launching site. At present the best solution is Kourou.

Other problems with such long duration BSO are the trajectory and the recovery of the gondolas. The better way to detect TGFs or/and TLEs in coordination with satellite measurements is to stay around the location of the cloud expanses. As a matter of fact, the probability of a “safe” recovery of the gondola is better when staying close to the launching place, or at least above lands. It is impossible to predict accurately the 10-days trajectories, and the probability of ending the flight above mountains, tropical forest or even the sea is high. Thus, we must accept to lose the gondolas, so at least two versions of the same instruments will be necessary to perform several flights during the lifetime of ASIM and TARANIS missions. This is not a problem for small and “low cost” instruments but could be a severe constraint for SPIRIT and TGF instruments both in the total cost of the project and in the manpower needed to build the instruments.

To decrease the probability of losing the gondolas, we can try to conduct the measurements during period of the year when the speed of the stratospheric winds is low.

The complexity of the project, its cost, and the CNES launching team availability will probably limit the number of the campaigns performed during the project. An optimal scenario will be one campaign every 18 months. Technical flights of the long duration BSO with instruments onboard must be conducted before the TARANIS launch, in order to maximize the probability of the success of the campaigns. Then, the technical flights could be conducted in more convenient places like Kiruna above the north polar cap, without being strongly limited by the trajectory, the period of the year and the recovery.

Finally, ground-based observations conducted close to the area of measurements will be necessary to better document the TLEs detected by the balloon instruments. In particular, coupling the two sets of observations of the same event will allows us to determine its location; We propose to use the already existing automatic cameras that are perform successful ground-based observations of various TLE events.

6. CONCLUSION

The instrumentation of the project is now well defined, as well as the measurements strategy and the launching site. Some works are now conducted with the CNES balloon division to propose the telemetry system, the onboard data processing, the electric power needed by the instruments and the possible mechanical structure of the gondola. Then, the final version of the project will be submitted to CNES in the frame of the next CNES call to proposals for balloon project;

Such ambitious project that involves a large multidisciplinary scientific community will strongly improve the scientific return of TARANIS, as well as the one of the ASIM and JEM-GLISM experiments on ISS. It could be a nice challenge for the European balloon activity.

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7. REFERENCES

1. Blanc, E., F. Lefeuvre, R. Roussel-Dupré, J.A. Sauvaud, TARANIS: A microsatellite project dedicated to the study of impulsive transfers of energy between the Earth atmosphere, the ionosphere, and the magnetosphere, *Adv. In Space Res.* **40**, 1268-1275, 2007.

2. Smith, D.M., L.I. Lopez, R.P.Lin et al., Terrestrial gamma-ray-flashes observed up to 20 Mev, *Sciences* **307**, 1085-1088, 2005.

3. Renard, J.-B., S. Bekki, P.-L. Blelly, Q. Bourgeois, G. Berthet, and A. Hauchecorne, .Analysis of the spatial distribution of the unusual NO_2 enhancements in the Arctic polar upper stratosphere and mesosphere observed by GOMOS-Envisat on January-March 2004, *J. Geophys. Res.,* in press.

4. Mironova, J. A., L. Desorgher, I. G. Usoskin, E. O. Flückiger, and R. Bütikofer, Variations of aerosol optical properties during the extreme solar event in Januray 2005, *Geophys.. Res. Letters* **35**, L18610, doi: 10.1029/2008GL035120, 2008.

5. Neubert, T., M. Rycroft, T. Farges, E. Blanc, O. Chanrion, E. Arnone, A. Odzimek, N. Arnold, C.-F. Enell, E. Turunen, A. Mika, C. Haldoupis, R. Steiner, T. Bösinger, O. van der Velde, S. Soula, P. Berg, F. Boberg, P. Thejll, B. Christiansen, M. Ignaccolo, P. T. Veronen, M. Füllekrug, J. Montanya, and N. Crosby, Recent results from studies of electric discharges in the mesosphere,

Surv. in Geophys. **29**, No. 2, 71-137, March 2008, DOI 10.1007/s10712-008-9043-1.

6. Neubert, T., T. H. Allin, E. Blanc, T. Farges, C. Haldoupis, A. Mika, S. Soula, L. Knutsson, O. van der Velde, R. A. Marshall, U. Inan, G. Sátori, J. Bór, A. Hughes, A. Collier, S. Laursen, and I. L. Rasmussen, Co-ordinated observations of transient luminous events during the EuroSprite2003 campaign, *J. Atm. Solar-Terr. Phys*. ***67*****,** 807-820, 2005.

7. Chauzy, S., J.C. Médale, S. Prieur and S. Soula, *J. Geophys. Res.* **86**, D12, 22,319-22,326, 1996.

8. Renno, N. O., J. F. Kok, H. Kirkham, and S. Rogacki, A miniature sensor for electrical field measurements in dusty planetary atmosphere, J. of Physics (Conference Series) 142, 012075.

9. Cummer , S.A., U.S. Inan, T.F. Bell et al., ELF radiation produced by electric currents in sprites, *Geophys. Res. Lett.* **25**, 1281-1284, 1998.

10. Van der Velde, O., A. Mika, S. Soula, C. Hadoulpis, T. Neubert and U.S. Inan, Observations of the relationship between sprite morphology and in-cloud lightning process, *J. Geophys. Res.* **111**, D15203, doi:10.1029/2005JD006879, 2006.

11. Renard, J.-B., M. Chartier, C. Robert, G. Chaluneau, G. Berthet, M. Pirre, J.-P. Pommereau, et F. Goutail, SALOMON: a new light balloon-borne UV visible spectrometer for night-time observations of stratospheric trace gas species, *Applied Optics* **39**, 3, 386-392, 2000.

12. Berthet, G., J.-B. Renard, V. Catoire, M. Chartier, C. Robert, N. Huret, F. Coquelet, et Q. Bourgeois, Remote sensing measurements in the polar vortex: comparison to in situ observations and implications for the simultaneous retrievals and analysis of the NO_2 and OClO species, *J. Geophys. Res*. **112**, D21310, doi:10.1029/2007JD008699, 2007.

13. Moreau, G., C. Robert, V. Catoire, M. Chartier, C. Camy-Perret, N. Huret, M. Pirre, L. Pomathiod, et G. Chalumeau, SPIRALE: A multispecies in situ balloon-borne instrument with six tunable diode laser spectrometers, *Applied Optics* **44**, 5972-5989, 2005

14. Huret, N., M. Pirre, A. Hauchecorne, C. Robert, et V. Catoire, On the vertical structure of the stratosphere at mid-latitude during the first stage of the polar vortex formation and in polar region in presence of a large mesospheric descent, *J. Geophys. Res* **111**, D06111, doi:10.1029/2005JD006102, 2006.

15. Joly, L., C. Robert , B. Parvitte, V. Catoire , G. Durry, G. Richard , B. Nicoullaud, V. Zéninari, Development of a spectrometer using a cw DFB quantum cascade laser operating at room temperature for the simultaneous analysis of N_2O and CH_4 in the earth's atmosphere, *Appl. Opt.*, in press, 2009.

16. Robert, C., Simple, stable, and compact multiple-reflection optical cell for very long optical paths, *Applied Optics* **46**, 5408-5418, 2007.

17. Mende, S.B., Y.S. Chang, A.B. Chen, et al., Spacecraft based studies of transient luminous events, sprites, elves and intense lightning discharges, in: Fullekrug, M., Mareev, V.A., Rycroft, M. (Eds.), *NATO Science series*, Mathematics, Physics and Chemistry, Springer, Heidleberg, pp 123-150, 2006.