

The 2011 Draconids: The First European Airborne Meteor Observation Campaign

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Abstract On 8 October 2011, the Draconid meteor shower (IAU#8, DRA) was predicted to cause two brief outbursts of meteors, visible from locations in Europe. For the first time, a European airborne meteor observation campaign was organized, supported by ground-based observations. Two aircraft were deployed from Kiruna, Sweden, carrying six scientists, 19 cameras and eight crew members. The flight geometry was chosen such that it was possible to obtain double-station observations of many meteors. The instrument setup on the aircraft as well as on the ground is described in full detail. The main peak from 1900-dust ejecta happened at the predicted time and at the predicted rate. The second peak was observed from the earlier flight and from the ground, and was caused most likely by

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trails ejected in the nineteenth century. A total of 250 meteors were observed, for which light curve data were derived. The trajectory, velocity, deceleration and orbit of 35 double station meteors were measured. The magnitude distribution index was high, as a result of which there was no excess of meteors near the horizon. The light curve proved to be extremely flat on average, which was unexpected. Observations of spectra allowed us to derive the compositional information of the Draconids meteoroids and showed an early release of sodium, usually interpreted as resulting from fragile meteoroids. Lessons learned from this experience are derived for future airborne meteor shower observation campaigns.

Keywords Meteors · Draconids · 21P/Giacobini–Zinner · Comet dust trail · Orbit · Atmospheric entry · Double-station observations · Spectroscopy

1 Introduction

1.1 Introduction to the Draconids

The Draconids meteor shower (IAU#8, DRA—also known as early October Draconids) occurs every year in early October with varying meteor rates. The dust particles originate

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from the Jupiter-family comet 21P/Giacobini–Zinner. The meteoroids impact Earth at a slow 23 km/s apparent entry speed (20 km/s geocentric entry velocity). Jacchia et al. (1950) did notice that Draconids look “soft” compare to other meteors, from the short duration and the high height of the meteors observed during the 1946 storm. Ceplecha and McCrosky (1976) classified fireballs according to their end height into groups I, II, IIIA, IIIB. The Draconids belong to the most fragile group IIIB (highest end point for a given velocity and mass). Ceplecha (1967) classified meteors according to their beginning heights into four groups A, B, C, D. It was found again that the Draconids belong to the most fragile group D (highest beginning point for a given velocity). More recently, several authors [including e.g. Borovička et al. (2007)] estimated bulk density and/or mechanical strengths of Draconids and concluded that these values are really very low. Thus, they probably represent one of the most pristine material for a scientific study of the early solar system.

The Draconid shower is known for dramatic meteor storms and smaller outbursts, with the most prominent storms in 1933 and 1946, when reported rates were 10,000 meteors per hour (Jenniskens 1995). Further outbursts occurred in 1952, 1985, 1998 and 2005 with lower meteor activity than in the previous years (Nakano et al. 1985; Yoshida et al. 1998; Watanabe et al. 1999; Campbell-Brown et al. 2006). The 1952 outburst was only detected by radar. The 1985 outburst came unexpected. Eastern Asia was best positioned for the 1998 outburst, which peaked at a different time than predicted by most then current models. Observations were made in the USA and Japan (Jenniskens 2006). The 2005 outburst, caused mainly by tiny particles, occurred during daytime, making it observable only by radar techniques (Campbell-Brown et al. 2006). Only the descending branch of the 2005 outburst (end of the outburst) was recorded in Europe due to late dusk. Double station video observation was carried out at that time in the Czech Republic (Koten et al. 2007).

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It remains unknown what exact years of dust ejecta are responsible for the different outbursts. Dust trail models of this short-period stream needed validation with better observations. Outbursts are predicted by integrating the orbital paths of meteoroids forward in time, once their initial position around the comet is described and the orbit of the comet is known. Future outbursts can be predicted by integrating the orbital paths of meteoroids forward in time, once their initial position around the comet is described and the orbit of the comet is known. Independent models successfully predicted the 2011 Draconids outburst (Vaubaillon et al. 2011). The validity of these models was tested by correctly predicting the exceptional outbursts of 1933 and 1946, caused by trails ejected in 1900 and $1900 + 1907$. In October of 2011, Earth was predicted to cross again the dust trail of 1900. Europe would be well positioned to see this outburst and significant activity was expected. In addition, Earth would cross older dust trails in the hours prior to this peak, which could provide insight into the comet's activity in the year's before its discovery.

An airborne meteor observation campaign was organized, the first such airborne mission organized by European institutions. This article acts as an introduction to the special issue dedicated to the 2011 Draconids and to the more detailed articles, and presents an overview of the whole campaign. Earlier papers describe the preliminary results (Vaubaillon et al. 2012a, b; Kotten et al. 2012). In this final report, we elaborate on the results from the campaign. Now the data analysis is complete and we discuss the lessons learned.

1.2 Introduction to the Comet 21P/Giacobini–Zinner

The comet was discovered by Mr. Giacobini from Nice (France) in 1900, shortly after its orbit was changed by a close approach with Jupiter in 1898, which evolved into an Earth crossing orbit. This made an easy target to observe, since it has been an Earth-crossing object ever since. This is the reason of today's Draconid meteor shower and especially Draconid outbursts. Indeed, the Earth can potentially enter a young meteoroid trail ejected by the comet. It is today a Jupiter-family comet with a period of 6.6 years, an inclination of 31.9° and an eccentricity of 0.707. Its heliocentric velocity at 1 AU makes it the source of the slowest shower meteors, with a geocentric velocity of about 20 km s^{-1} . It was rediscovered in 1913 by Mr. Zinner from Bamberg, Germany, and since then it carries the name 21P/Giacobini–Zinner.

It is unclear whether the change in orbit caused unusual activity of the comet in 1900. The comet now is hyperactive, showing both water and CO₂-driven ejection of dust, and may be a relatively recent capture by Jupiter. In 1985, it was the target of the International Comet Explorer spacecraft, and extensive measurements of the plasma in the ion tail were performed Gurnett et al. (1998). Although it was found to be extremely depleted in small carbonaceous molecules (C₂, CN) by A'Hearn et al. (1995), the meteoroids may contain complex organic matter instead, based on results from polarized observations of the cometary dust Kiselev et al. (2000). As such, the Draconid meteors can be the most efficient way today to bring organic matter into the Earth atmosphere.

1.3 Summary of the Prediction of the 2011 Draconids Outburst

The prediction of the outburst of a meteor shower has been a challenging problem until 1999, when McNaught and Asher (1999), following Kondratieva and Reznikov (1985) showed that meteoroids are dynamically independent from the orbit of the comet, once they are released. Since then, the prediction of meteor showers outbursts has become routine. The more modern models also attempt to predict the distribution of the dust in the Earth's

path and the level of activity. Those models need an understanding of the conditions during ejection of the comet. Although comet ejection models have become more sophisticated, the prediction of peak activity is still the most difficult today.

The prediction of the 2011 Draconids outbursts were performed several years before the event. A summary of all the different predictions for the 2011 Draconids is given by Vaubaillon et al. (2011), and some additional material was provided by Asher and Steel (2012). The timing of the main outburst (caused by the 1900 trail) was pretty well known in advance, thanks to the dynamical simulations, and was estimated between 19:30 and 20:30 UTC. The activity level of the outburst was more difficult to predict, especially because the past Draconid storms from encounters with the same dust trail were not well observed and also because of uncertainties about the comet large grain dust ejection conditions from the past photometric measurements of the comet. Watanabe and Sato (2008) argued that a change of activity of the comet had to have occurred to explain the high past observations of Draconid storms.

Figure 1 shows the location of the meteoroid stream in the vicinity of the Earth at the time of the maximum of the outburst. Two outbursts were predicted on 8 October 2011. The first one was presumably from old trails, ejected before the discovery of the comet, during the nineteenth century. These predictions were based on the backward propagated orbital data of the comet during its first detection in 1900. The second one was caused by the 1900 trail, which was also responsible for the 1933 and 1946 storms. As a consequence, the 2011 Draconids outburst provided us with the opportunity to fully characterize and calibrate the past observations, provided that the modeling of the evolution of the meteoroid trail in the solar system is correct.

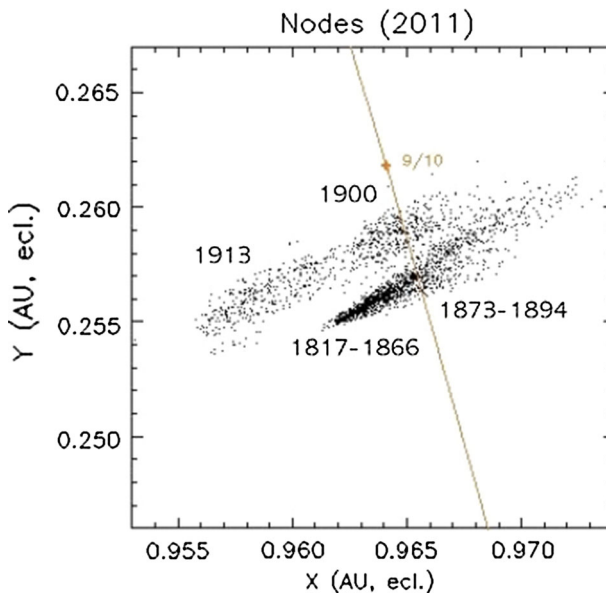


Fig. 1 Predictions of the 2011 Draconids. The *line* shows the path of the Earth, and the *dots* show the location of the node of the meteoroid stream. We can see that the Earth will encounter two different trails, on 8 October 2011

2 The First European Meteor Observation Campaign

2.1 The Interest of Airborne Meteor Observation Campaign

Although low level meteor outbursts are not unusual, strong meteor outburst is usually a unique and exceptional event. For the record, the previous Draconids outburst occurred in 1933, 1946, 1985, 1998 and 2005. In order to make the most of such a unique event, exceptional observation means are required.

Airborne based meteor observation campaigns were organized in the past for several reasons (Jenniskens 2002). First, they guarantee the success of the observation by putting all the observational equipment above the clouds. When the magnitude distribution index is low, they also guarantee 4–5 times higher rates of meteors, mostly in a 5–10° band near the horizon. Such advantage does not occur, however, when the magnitude distribution index is high as was the case during some past Draconid showers. From a logistic perspective, an airborne observing campaign can put the observers at the optimum location on the surface of the Earth, ideally under the radiant, for the duration of the observations. The flexibility of an airplane concerning the location of the observers is therefore a tremendous advantage. The guarantee of clear weather and ideal observing conditions can motivate participation of a “dream team” of meteor scientists, as well as a multiplicity of different instruments in order to fully grasp the meteor phenomena. Besides airborne campaigns, space-based optical system may be considered for meteor monitoring (Christou et al. 2007; Oberst et al. 2011; Bouquet et al. 2014). On the other hand, airborne based endeavor usually takes much more preparatory time than ground based deployment, including finding the funds to fly the aircraft (a few k€ per aircraft). The installation of the cameras into the aircraft takes some time, and test flights are necessary to validate the observation procedure. Safety checking is of course drastic. The timing of the observation itself is similar to ground based approach, in the sense that the outburst happens once and cannot be reproduced, as often in Solar system astronomy.

2.2 Why a European Campaign?

Even though European scientists have participated in multi-instrument airborne meteor observation campaigns in the past, they had never organized such an event before. The 2011 Draconids airborne campaign was therefore the first campaign using airplanes organized by European and performed by Europeans. This was possible thanks to the French laboratory Safire as well as the German DLR, both operating a Falcon 20 for research purposes, respectively registered as F-GBTM and D-CMET. The German aircraft was kindly provided thanks to the European Facility for Airborne Research (EUFAR), an Integrating Activity of the 7th Framework Programme (FP7) of the European Commission, aiming to provide research aircraft facilities to European countries that do not have easy access to such a system.

The 2011 Draconids outburst occurred on a Saturday evening, and was visible in most parts of the European countries. Of course, a meteor outburst is an international event, and thanks to existing scientific collaborations, several instruments from different countries were used during the airborne campaign. In addition, several teams were located on the ground at sites in Germany (Kuehlunsborn) and Southern Europe (Pic du Midi, Italy, Greece), in hope of clear skies. Amateur astronomers of the International Meteor Organization (IMO) were active at observing the meteors throughout Europe.

2.3 Scientific Goals of the Campaign

The scientific goals of the campaign were to witness this unique outburst, and record it with proper scientific tools to keep track of what happened. Because the 1933 and 1946 Draconid storm observations were not measured with the same tools and methods as today, the 2011 Draconids could provide insight into that past meteor shower activity. From this, the suggestion that the comet activity had changed over time could be verified, in particular whether or not the change in orbit following the 1898 encounter with Jupiter had an effect on the comet activity. In addition, the first 1800's-dust peak, if observed, would provide information about the orbit and level of activity of the comet before its discovery in 1900. The 2011 Draconids would provide information about the dynamics of the comet more than 112 years before the event itself. The meteor observations could also provide insight into the physical and compositional properties of the dust of comet 21P/Giacobinni–Zinner, information that would otherwise require a sample return mission. It is therefore a good way to test the prediction models as well as the orbital data of a comet. Alternatively, such an observation can also tell us about the evolutionary activity of the comet. Last but not least, the composition of the cometary grains ejected more than 100 years ago is accessible when they disintegrate in the atmosphere. The observation of meteor showers are therefore a nice proxy and alternative to the costly sample return missions. Ultimately, the survival of organic matter from comet 21P, if detected, can tell us about the influence of the meteors on the composition of the early Earth atmosphere, and the spread of organic molecules in the whole solar system until today.

2.4 Flight Plan and Airborne Configuration

Because of the location of the radiant of the Draconids, we decided to deploy the aircraft at an accessible northern airbase in Europe. Kiruna, Sweden was selected for its facility, as well as the possibility to take off and land at accurate timing, thanks to the relative absence of traffic at this time of the year and of the day.

A meteor outburst usually lasts for several hours. Because the flight time of these particular aircraft is limited to four hours, we decided to split the observation into two legs. The first leg was intended to observe the first peak, and we initially planned to fly over Russia, but that proved too difficult to accomplish. We did not receive the clearance for this flight, so we changed the flight plan a few days prior to the deployment to Sweden to an alternative flight route developed by NASA Ames Exploration Academy student Jon Reijneveld of the Technical University of Delft. This brought us over Finland, up to the Russian border, and then back to Kiruna for a refuelling. The flight plan to observe the first peak is shown in the Fig. 2. It was observed from the air with the French Safire aircraft. The DLR aircraft received funds for the second leg only. In spite of this restriction, the DLR Falcon scientific crew was able to observe from the ground during the time interval 17:00–18:28 UT, using the cameras already deployed on board the aircraft. With this setup, 16 Draconids and 5 sporadic meteors were recorded.

For the second peak, which was the most important, the two aircraft were flying together in order to conduct double station observations. The observation from the air was performed in time interval 19:15–21:44 UT. The planning of the double station experiment was complicated by the very bright Moon towards the south. We wanted to avoid aiming the cameras (especially image intensifier cameras) close to this bright source of light. We chose to keep the observing conditions constant during the peak of the shower by flying west, keeping the Moon at a constant position in the field of view. The Moon was on the

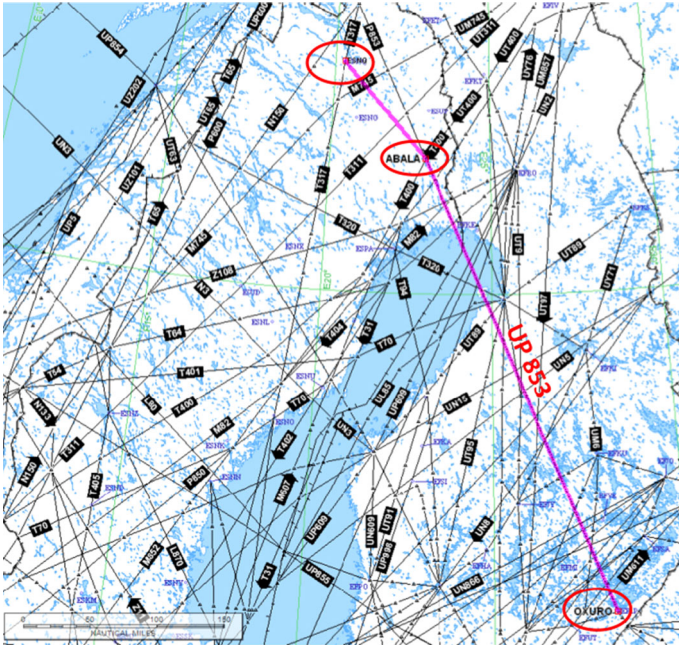


Fig. 2 Flight plan of the airborne campaign to observe the first peak

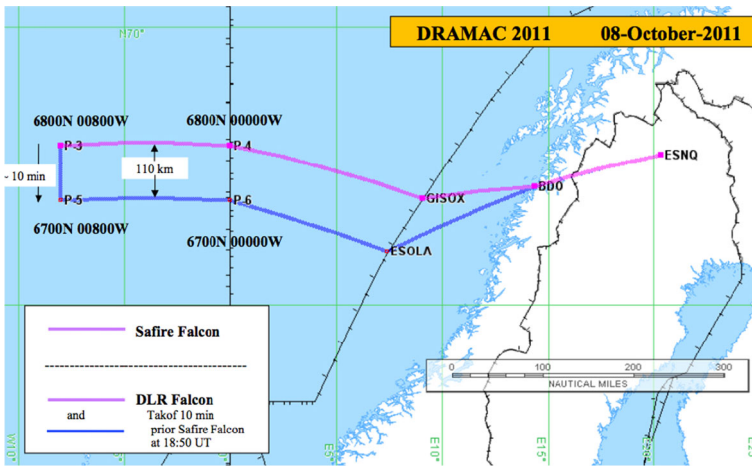


Fig. 3 Flight plan of the airborne observation to observe the second peak

left-hand side of the plane on the way out, and on the right-hand side on the way back. It kept a relative constant position during each leg, but also created parasite lights, especially for spectroscopy measurements. The flight plan is shown in Figure 3.

The configuration of the two aircraft in order to conduct double station observations was optimized as to minimize the time during which the aircraft were making a 180° turn to

come back to base. Figure 4 shows the configuration of the two aircraft on the first leg (way in) of this flight. The distance between the two aircraft was approximately 110 km. The overlap of the two fields of view ensured a double station observation. For the second leg (way back, Fig. 5), the two aircraft were flying in formation, separated by a 100 km distance. Each aircraft was operated by a pilot, copilot, mechanics, onboard system engineer as well as a three meteor scientists. In total 19 cameras were deployed in the two aircraft altogether.

In order to reconstruct the 3D trajectory and orbit of meteors, the determination of the position—velocity of the camera are needed. Each aircraft was equipped with inertial facility, providing the location (longitude, latitude, altitude) and orientation (heading, pitch

Fig. 4 Schematic view of the serial airborne configuration during the first leg (way in) of the double station observation of the second peak

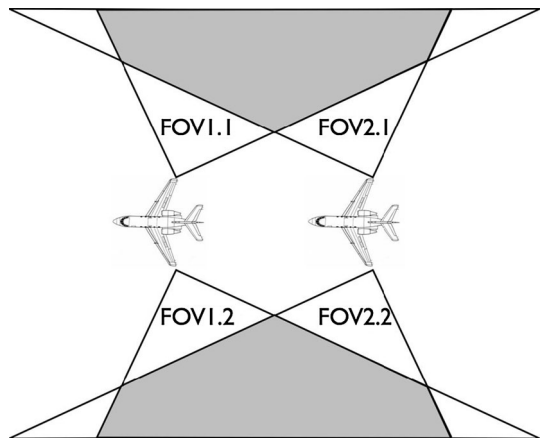
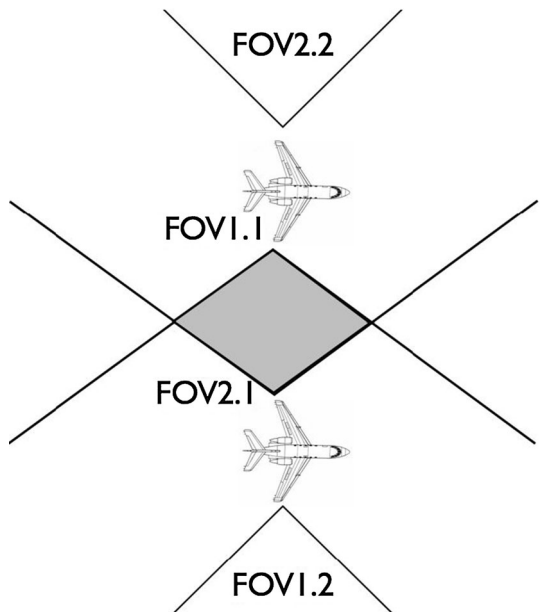


Fig. 5 Schematic view of the parallel airborne configuration during the second leg (way back) of the double station observation of the second peak



and roll angles) at 100 Hz, as a function of a GPS clock. The flight coordination between the two aircraft was a major requirement for the success of the operation, in order to maintain an almost constant distance between the cameras (otherwise it would be impossible to achieve double-station observations).

2.5 Instrumental Set Up

The principle of a meteor multi-instrument aircraft's observation campaign is to set up cameras in front of the aircraft windows and to continuously record the signal during the duration of the shower. In practice, each airborne facility has its own policy for the instrument deployment. In the Safire aircraft, all the cameras were fixed on racks, allowing us to start the observation and the setup of all the computers even before take off. In the DLR aircraft, on the contrary, all the instruments were packed during the take off and landing phases of the flight, and unpacked shortly after take off. No rack was available, so we had to use separate tripods to fix the cameras in front of the windows. The advantage of such a solution is the flexibility to move the instruments from one side of the aircraft to the other, as a function of the heading of the aircraft and the desired pointing directions of the camera. However, this requires a perfect knowledge of the operation and assembly of the cameras to be moved, as well as a perfect coordination between the different operators moving the instruments.

The choice of the instruments was led by the multiplicity of the scientific data they allowed us to record. High sensitivity video rate cameras (type Watec) were used for counting the meteors as well as measuring the 3-D trajectory, by coordination of the fields of view in the two different planes, as well as for obtaining the spectra. Video cameras equipped with image intensifiers were used for the same applications, as well as for the recording of fainter meteors, allowing us to derive the population index, and for all-sky monitoring (Koten et al. 2011; Tóth et al. 2008, 2011). Highly sensitive E2V CCD still cameras (SPOSH, Oberst et al. 2011), taking one image every two seconds, as well as the AMOS cameras (Zigo et al. 2013; Toth et al. 2013) were efficiently used for all sky monitoring. So-called CABERNET-type cameras (Atreya et al. 2012) were used but did not provide any satisfactory results, mainly because the constant aircraft roll is incompatible with long time exposure (1 s). They were used with 0.7 s exposure time, but had a smaller field of view than the SPOSH camera. Thus the constant rolling of the aircraft caused the stars to trail in the images, making it impractical to analyse the data. Initially they were intended to measure accurate 3-D trajectory. In practice, one failed right at the time of the observation and the other one provided poor quality images for the reason quoted above. Figures 6 and 7 show the configurations of the cameras in the Safire aircraft. The fields of view were carefully computed in order to conduct double station observations. The coordinates (azimuth a and elevation e) of the center of the field of view were the following:

- 1st leg: DLR: $a = 210^\circ$ $e = 36^\circ$; SAFIRE: $a = 160^\circ$ $e = 40^\circ$
- 2nd leg: DLR: $a = 220^\circ$ $e = 55^\circ$; SAFIRE: $a = 330^\circ$ $e = 50^\circ$

2.6 Ground Based Observations

In support of the airborne campaign, ground-based observations took place at different locations over Europe. Double station observations were set up at the Observatoire de Haute Provence, France as well as on Rhodos Island in Greece (Leroy et al. 2013). Double

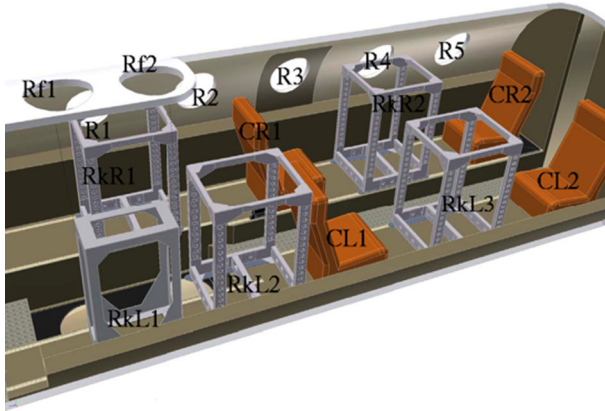


Fig. 6 Camera configuration in the French Safire aircraft. The different labels indicate: *Rf1* roof window, not used, *Rf2* roof window 2: SPOSH, *R1* NHK HDTV camera, *R2* CABERNET, *R3* DSLR + $f/1.4\text{--}30$ mm, *R4*, intensified video camera, *R5*, Waterc + 12 mm $f/1.2$ and Waterc + 6 mm $f/1.2$, *RkL1* intensified video camera, *RkL2* Waterc + 300 l/mm grating, *CL1* DSLR + 50 mm $f/1.2$, *RkL3* Waterc + 6 mm $f/1.2$, *CL2* NIR video camera

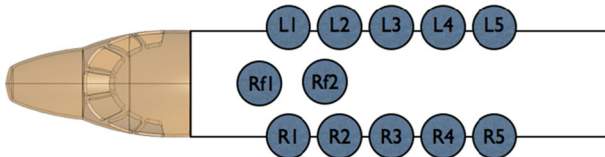


Fig. 7 Camera configuration in the German DLR aircraft. The *left hand side* was used during the first leg of the flight (way in), and the *right hand side* for the second leg (way back). The different labels indicate: *Rf1* roof window, SPOSH (failed), *Rf2* roof window 2: AMOS, *L1* CABERNET (failed), *L2* ESA-spectrum camera, *L3* Ondrejov observatory intensified video camera + spectra video camera, *L4* ESA-direct camera, *L5* not used (DLR aircraft technician set), *R1* unavailable, *R2* CABERNET (failed), *R3* ESA-spectrum camera, *R4* Ondrejov observatory intensified video camera + spectra video camera, *R5* ESA-direct camera

station observation was planned at the Pic du Midi observatory, France. Double station observations were carried out also in Northern Italy by Ondrejov observatory team using image intensifier video cameras and photographic cameras (see Borovicka et al. in this issue). Another team from Modra Observatory, Cement and Polish Meteor Network were deployed at northern Italy and coordinate multi-station video observations with local IMTN network (Toth et al. 2012, 2013). Single-station data was successfully recorded from a camera in Noordwijkerhout, The Netherlands. In addition, the CAMS system (Jenniskens et al. 2011) was deployed in Kühlungsborn, Germany, where LIDAR observations are possible.

Radio observations were performed in the Benelux area McBeath (2012), Calders et al. (2013), Toth et al. (2012, 2013). The 2011 Draconids were also observed with the Shigaraki middle and upper atmosphere (MU) radar in Japan as well as the CMOR radar (Kero et al. 2012; Ye et al. 2013).

Bad weather conditions did not allow us to observe from the Pic du Midi Observatory and Rhodos Island. Northern Germany experienced partial cloud cover during onset of the shower, but succeeded measuring over 20 multi-station Draconid trajectories and detected

several neutral atom debris trails. From the results obtained by several other authors, it looks like the ideal place for ground based observation of the 2011 Draconids was limited to West Southern Europe (Šegon et al. 2014; Molau and Barentsen 2013; Trigo-Rodríguez et al. 2013; Madiedo et al. 2013; Toth et al. 2012, 2013).

2.7 Data Processing

All the meteor showers data reduction processing starts with the detection of the meteors in all the gathered data. Usually, this is achieved thanks to the use of automated detection software, such as UFO capture or MetRec or ASGARD (SonotaCo 2009; Brown et al. 2010; Molau 1999, 1999). As the light turbulence caused the movement of the sky background during the flight, it was not possible to detect meteors by using any automated detection software. Therefore, continuous recording was performed by storing 2- or 5-min long movies (depending on the device). The detection of the meteors was performed “manually” by watching all the videos by at least two people for redundancy purpose. This is of course quite a tedious task, but it was accomplished within a few days, whereas it would take weeks to develop a program able to detect a meteor in a movie taken from a moving platform. Northern lights (Aurora) were present during the whole duration of the flights, and sometimes prevented us from detecting meteors, or interfered with the photometry data extraction of the meteors. The video sequence encoding the meteors were extracted individually for further processing. The location of the meteor in the image was measured for each frame. In order to produce astrometric calibration images, several images of the star field (not including the meteor) were stacked together, taking into account the shift of the stars in the image because of the motion of the aircraft. The astrometric output was corrected for precession, nutation and aberration (and sometimes refraction). The data were formatted in order to be processed by different softwares, so data can be shared and results may be compared. The timing of the meteors from different cameras were recorded by either inserting the time taken from the PC controlling the camera, or by GPS time inserter into video frame. However these features were not available for all settings, which made it difficult sometimes to dig identify double station of the same event. The very details of each and every data reduction procedure are included in the dedicated articles in this issue.

Three short workshops (3 days to 1 week) were organized to reduce the data, but a much larger amount of time was necessary to perform all the work.

3 Main Results

3.1 The 2011 Draconids Outburst

Koten et al. (2014) present a thorough analysis of the 2011 Draconid shower activity. The 1900-dust peak during the 2011 Draconids appeared exactly at the expected time, around 20 UT. The level of the shower reached 300 meteors per hour (after correction). The peak lasted about one hour, and the shower lasted a couple of hours in total. After carefully examining the data, it appears that the first peak caused by trails ejected before 1900 was detected. This tells us that the comet 21P/Giacobini–Zinner was active prior to its discovery in 1900, and that its orbit was very close to the orbital solution we had computed. This also shows the power of the observation of the meteor showers, since a couple of hours of data collection can tell us what happened to a comet more than 120 years prior to

the event. It is worth mentioning that the observation of the first peak from Europe was made possible thanks to the deployment of our instruments to the northern latitude, enabled by the airborne campaign. Other observation of this peak were reported in Canada (Vaubaillon et al. 2011; Ye et al. 2013) and Japan (Kero et al. 2012) with radar instruments.

3.2 Atmospheric Trajectory

During the entry of a meteoroid into the upper atmosphere, there are several major factors affecting its further trajectory. These factors include the meteoroid size, shape, and material properties, as well as its geocentric velocity vector. Thus the study of Draconids interaction with the Earth's atmosphere may be used to identify their physical and chemical properties, and to calculate the pre-atmospheric masses of the particles based on observations. As it was previously reported, the visual paths of Draconids are typically much shorter than average, with relatively low velocity values and high beginning heights (Jacchia et al. 1950; Borovička et al. 2007; Kero et al. 2012). Typically the meteoroid does not have a possibility to significantly decelerate under such conditions, and thus the mass loss process is dominant. In a number of cases, noticeable deceleration—i.e. a decrease of velocity for lower heights—was observed. The general difficulty is that average Draconids deceleration values are comparable to their own probable errors. Similar behaviour was reported by (Ye et al. 2013). Whenever the deceleration was observed, an equation of the form:

$$h/h_0 = \ln 2\alpha + \beta - \ln(\bar{E}i(\beta) - \bar{E}i(\beta V^2/V_e^2)) \quad (1)$$

was fitted by the least squares method to the observed heights, h , and velocities, V . The other parameters in Eq. (1) are the scale height, $h_0 = 7,16$ km, the pre-atmospheric velocity, V_e , and the sought parameters are the ballistic coefficient, α , and the mass loss parameter, β , as described in Gritsevich (2009). The exponential integral $\bar{E}i$ is calculated as described in Gritsevich and Koschny (2011). The dimensionless quantities α and β found in such a way are unique and specific for each meteor and they can be further used to resolve, for example, the problem of finding the pre-atmospheric mass and ablation coefficient values.

3.3 Surprisingly Flat Light Curves

The Draconids have been considered in previous literature as one of the most fragile meteoroid stream. E.g. Jacchia et al. (1950) have reported results of the Draconids observations in 1946 using photographic techniques where they found that the emitted luminous energy per unit mass is at least 100 times higher for the Draconids than for ordinary meteors. They note that the average height of the Draconids is lower than those of other meteor showers. They also noted that the average trail length is much shorter than those of meteors of other showers with similar brightness. They conclude that the meteoroids are more fragile than any other stream. Borovička et al. (2007) confirmed this by using measurements of seven Draconids recorded with stereoscopic video and photographic observations of the 2005 Draconids.

To interpret the luminosity of a meteor with evident deceleration signs, one may use approach described by Gritsevich and Koschny (2011). It is however difficult in the case of

current Draconids study due to the relative errors in deceleration values mentioned above. Thus, the light curve analysis has been conducted according to Borovička et al. (2007)

We have analyzed the single-station light curves of ca. 80 Draconids and computed the so-called f -factor ($f = 0$: Maximum brightness at the beginning of the path, $f = 1$: Maximum brightness at the end of the path) as defined in Fleming et al. (1993). A few meteors show quite flat light curves with no prominent peak; those meteors which do show a prominent peak have f -factors between 0.2 and 0.8. The average is 0.5. Flat light curves do not contradict fragile meteoroids. Strong meteoroids are not expected to show flat light curves. Fragile meteoroids may have various shapes of light curves depending on the process of fragmentation, which understanding is still to be refined. We conclude that the f -factor may not be a good indication for describing the fragility of meteoroids.

3.4 Meteor Spectra

Preliminary results are published in Borovička et al. (2013), Rudawska et al. (2013, 2014). 15 Draconids spectra were analyzed. All spectra show an early release of the sodium, similar to what was found in previous observations. This is interpreted as a consequence of the fragile nature of the Draconids meteoroid. Note that Borovička et al. (2013) reported differences when comparing several Draconid meteor structures. This points out the need for cross-analysis of meteor observation data and for further studies of our interpretation of data in general.

4 Lessons Learned and Future Plans

4.1 Lessons from What We Did Right

The success of the mission came in a great part from cooperation between scientists of the entire world. Many scientists contributed by sharing their instruments and/or expertise. Similarly, we made efforts to learn how to operate several cameras for which we had little or even no training before the organization of the campaign. However, we do recommend that each scientist take the time to master all different cameras before the events, in order to know exactly what to do, and not to confuse different procedures. Indeed, during the event, no time can be wasted, and the stress factor has to be taken into account in order to maximize and optimize the observation recording sequences.

The coordination between the pilots of the two airplanes as well as the strict respect of the timing allowed us to record many double station meteors, as well as to cover both peaks. This experience has shown that the flight plan can still be changed a few days prior to departure from the base. However, this is not recommended as flying and working over different countries usually necessitates many clearances. Once again, we cannot stress enough the need for preparation of such a campaign long time in advance and at least one year prior to the event. Such preparation should also include the data processing by each scientist, but also in groups, during workshops. This allows us to not only be much more efficient, but also to share data and results in a quick way. Similarly, the writing of all the articles is quickened by the organization of a dedicated workshop.

Although the flights did allow us to collect precious unique data, the power and the capabilities of a distribution of ground-based observers over hundreds of kilometres have also again proven to be extremely efficient. Indeed, at the end of the flight, the profile of the 2011 Draconids outburst was already available on the website of the International Meteor

Organization (IMO). This allowed us to know immediately that the predictions were correct and that we did collect many meteors during the flight. Because of a rolling movement of the plane, automated detection is not possible (unless the camera is a stabilized, which was not the case). As a consequence, unless performing a lot of dedicated manual work to visually count the meteors, it is nearly impossible to know the exact timing and the level of the shower observed during the flight. All this was made possible thanks to the previous experience of airborne observation campaigns and thorough discussions with the different actors.

We recommend that the flight plan takes into account the location of the radiant, the Moon and the Sun. Ideally, the aircraft should be positioned under the radiant. Since this is not always possible, the plane should fly in a direction facing or directly away from the radiant. Similarly, the plane should fly directly facing or away from the Moon. During the observation, the plane should be at a location where the Sun is 18° under the horizon (astronomical night). The height of the Sun below the horizon has to be computed taking into account the altitude of the aircraft. In practice, it is actually extremely hard to cope with all these restrictions.

4.2 Lessons from What We Could have Done Better

To this day, we are still debating over the quality of the flight plan, which was a compromise between all the restrictions mentioned above. The initial plan allowed us to work at a constant elevation of the radiant during the whole observation set. However, the Moon was close to the field of view of the cameras located on the side of the aircraft facing South. This was especially painful for the spectroscopy observation, since the Moon high orders spectrum ended up falling inside the field of view. The change of strategy for the first leg ended up to work out well for the observation, by putting the Moon in front of the aircraft, far from the field of view of the camera.

A better coordination between the camera dedicated to the measurement of the 3-D trajectory (and the orbits of the meteors), and the camera dedicated to spectroscopy measurements would have helped us to fully and better interpret the spectra.

The multiplicity of different instruments to be operated by one scientist have underlined the necessity to fully train in order to fully master all different procedures. In any case, the human factors should not be neglected. During this campaign, we lost 30 minutes of observation time for one camera because of human mistake.

A few cameras did not work properly, not only during the campaign because of unexpected damage (which, by nature, cannot be predicted), but also before the campaign. As a result, some scientists spent a non-negligible time trying to fix the camera. This kind of technical problem is actually hard to anticipate, especially for a material that is working well most of the time. However, as much as it is possible, a camera that is known to possibly cause problems should not be considered to fly.

When planning campaigns close to the Arctic circle, the negative effect of aurorae on the observations should not be neglected. We have experienced in this and other campaigns a significant increase in the sky background due to aurorae.

During the data reduction, one big issue was the timing of the meteors. Because of the multiplicity of material used for such a campaign, it is not straightforward to have a unique way of dating the images. Lot of time was spent to find the same meteor from different datasets.

Last but not least, unless it is stabilized, long time exposure cameras [more than 1/10 of a second, such as the CABERNET camera Atreya et al. (2012)] used with narrow field

lenses has proven not to provide useful scientific data, because of the constant rolling of the aircraft.

4.3 Summary of all Recommendations for Future Meteor Shower Airborne Campaign

On the basis of our experience, here is a list of our recommendations for future meteor shower airborne campaigns. These recommendations are provided in order to organize a perfect observation campaign. However in reality, these recommendations may not be attainable all at once. Our experience shows that great science can still be achieved even when not all these criteria are met, usually for practical reasons.

4.3.1 Organization

Thorough discussion with the aircraft facility members and the crew has to start early enough prior to the event in order to clarify the scientific goals and the way to achieve them, as well as to plan the coordination with other aircraft. The exact amount of time prior to the event highly depends on the aircraft facility and funding procedures. In our case, we started the discussions one year before the 2011 Draconids, but it can be reduced to a few days when procedures are flexible. When the cameras are fixed in the aircraft prior to the flight, the orientation of the camera inside the plane has to be decided in advance as well, in order to optimize the observation and the scientific return of the mission. This in turn, allows the coordination with the instruments inside another aircraft. This is of course especially true for trajectory and the orbit determination, but also for spectroscopical measurements. The clearance to fly over in many different countries has to be obtained before the campaign. The exact amount of time (in our case, a few weeks) greatly depends on the country procedures flexibility.

4.3.2 Flight Plan

The flight plan has to take into account the location of the radiant, the Moon and the Sun. Ideally, the aircraft should be positioned under the radiant. Since this is not always possible, the plane should fly in a direction facing or directly away from the radiant. Similarly, the plane should fly directly facing or away from the Moon. During the observation, the plane should be at a location where the Sun is 18° under the horizon (astronomical night). The height of the Sun below the horizon has to be computed taking into account the altitude of the aircraft. In practice, it is actually extremely hard to cope with all these astronomical restrictions. Usually, the Sun is not a problem, but the location of the radiant and the Moon is the cause of a compromise. Aircraft observation campaign have showed that such a compromise can be found in all cases. Where possible, regions with aurorae should be avoided when planning a meteor observation airplane campaign.

4.3.3 Flight Configuration

The configuration of the two aircraft can be either serial or parallel. Depending on the configuration, the pointing direction of the cameras has to be carefully computed in order to ensure the coordination between them and the overlap of the field of view from both aircraft.

4.3.4 Procedures

Instruments should be shared by different scientists in order to maximize the diversity of the measurements. The scientist operating the different instruments should familiarize him/herself already before the campaign on ground with the acquisition and data reduction procedures, ideally a few months to weeks prior to the campaign. If possible, an in-flight rehearsal of the observations, e.g. the night before the actual campaign, should be performed in real observation conditions. Ideally, the rehearsal should also include the operation of all the different cameras at a time, in order to be familiar with the induced stress factor, as well as to evaluate the limitation of the operator and plan the observation procedures accordingly. Similarly, the procedures should take into account the failure of one system and a backup plan in order to optimize the rest of the observation. Ideally, redundancy of the observation means is recommend, but is not always feasible in practice.

4.3.5 Data

The data have to be continuously recorded, since usually, the meteor detection software is of no use because of the constant rolling of the aircraft. The dating of the data is mandatory and should be accurate to the second at worse. GPS time is usually available inside the aircraft, through NTP server. However, this is of no use in case of video tape recording for which another solution should be found. GPS data video inserter is one solution and was used during this campaign for several (but not all) cameras and in the NASA campaigns. Data format conversion or harmonization should be established before the campaign to ease the data analysis.

4.3.6 Stabilization

Providers of long-time exposure cameras should consider stabilization of their instrument. If that is not possible, they should be replaced by faster cameras. Stabilization can be a real added value for double station observation of meteors, by making sure the field of view is constant and allowing the measurement of photographic meteors (providing a higher accuracy in terms of trajectory). To our knowledge, such a technology has still to become mature (e.g. prove to be failsafe) in order to recommend its use for airborne meteor observation campaigns.

5 Conclusion

This first European airborne meteoroid observation campaign was a real success. It benefited greatly from past airborne observation campaigns organized by NASA Jenniskens (2002, 2001), Jenniskens et al. (2006); Jenniskens and Hatton (2008). We demonstrated that existing European aircraft facilities usually used for the remote or in situ sensing of the atmosphere can be used successfully for meteor shower observations.

The 2011 Draconids meteor outburst was the occasion for dozen scientists to collaborate on a common project. The outburst occurred at the predicted time, showing once more that the forecasting of the meteor showers are reliable, as long as the parent body is known. The detection of the first peak showed that meteor science can be used as a way to probe the comets prior to their discovery. The flat light curve observed on average show the diversity of the cometary grains ejected by Comet 21P/Giacobini–Zinner. Further investigations are needed to fully understand its reasons. However, this is consistent with the diversity of

composition observed in grains detected by Stardust around comet 81P/Wild 2 Zolensky et al. (2006), a priori reflecting the mixing of chemical species in the early Solar System.

We list here the scientific goals of the campaign and compare them to our achievements.

5.1 Observations

The airborne campaign allowed to observe the two peaks with optical means, with double stations setup allowing to measure the orbits of some Draconids (Koten et al., in preparation). Dynamics: the occurrence of the outbursts confirmed the forecasting, including the fact that comet 21P was active before its discovery, and on an orbit very similar to the theoretical one (otherwise, no first peak would have been observed). Past comet activity: the level of the first peak indicates that the comet was not as active as after its orbit changed, otherwise it would have been much higher, because of the accumulation of the dust for several perihelion passage. Insight into past Draconids storms: the level of the main peak was not as high as expected. Different explanations are suggested: (1) past observation reports need to be re-analyzed in the light of modern techniques (2) the 1900 trail experienced meteoroid loss by a yet to be determined mechanism (3) the distribution of particles inside the trail is not as expected (4) a combination of any of those hypothesis. In any case, this calls for further work. Composition: the fragile nature of Draconids seems to be confirmed once again from the early release of sodium. However, further interpretations can also be derived Borovicka et al. (2013). Organic matter was not reported, but specific search was not conducted either. Unexpected results: the most surprising result is the abundance of flat light curves during the 2011 Draconids.

Our experience of airplane meteor outburst observation campaign keeps increasing in quality, thanks to the multiplicity of the campaigns and dedicated volumes gathering all the knowledge of such topic. When the Leonid meteor storms comes back, starting in 2032, we will definitely be ready.

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