The Southwestern Europe Meteor Network: recent advances and analysis of bright fireballs recorded along April 2021

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We present here some recent improvements performed in the framework of the Southwestern Europe Meteor Network (SWEMN) and the SMART project. In particular, we focus on the development of the first digital database dedicated to meteor events recorded over Spain and neighboring areas. This includes, among other information, the circumstances of each event, orbital data, emission spectrum, lightcurve, and meteoroid physical properties. We also discuss in this work the main fireballs recorded by our network along April 2021.

1 Introduction

The Southwestern Europe Meteor Network (SWEMN) is a research project coordinated from the Institute of Astrophysics of Andalusia (IAA–CSIC) with the aim to analyze the Earth's meteoric environment. This network is also integrated by researchers from the Complutense University of Madrid (UCM), the Public University of Navarre (UPNA), and the Calar Alto Observatory (CAHA). In order to identify and analyze meteors in the Earth's atmosphere, SWEMN develops the Spectroscopy of Meteoroids by means of Robotic Technologies (SMART) survey (Madiedo, 2014; Madiedo, 2017).

To improve our knowledge about the Earth-Moon meteoric environment, SMART works in close connection with another project conducted by IAA–CSIC: the MIDAS survey (Moon Impacts Detection and Analysis System). MIDAS uses the Moon as a laboratory that provides information about meteoroids hitting the lunar ground (Ortiz et al., 2015; Madiedo et al., 2018; Madiedo et al., 2019a). A strong synergy has been proved to exist between this survey and the SMART project (Madiedo et al. 2015a,b; Madiedo et al. 2019b).

This work focuses on two new steps taken in the framework of SWEMN. The first of these is our openness to the amateur astronomy community. The second step involves the development of the first comprehensive digital database containing information about bolides and meteors recorded over the Iberian Peninsula, and the software tools necessary to exploit this new resource. In addition, as in previous reports (see for instance Madiedo et al., 2021), we also discuss here the most remarkable bolides recorded during April 2021 by our systems.

2 Pro-Am collaboration

The SMART survey was started as a professional project in 2006 (Madiedo, 2014; Madiedo, 2017). Since then, the results obtained in the framework of this project and the most remarkable fireballs recorded by our meteor stations have been widely disseminated among the public, mainly through social networks, media and conferences. In particular, YouTube, Facebook and Tweeter have played a key role in our outreach activities. These have contributed to increase the interest of the public in Spain for meteor science. And, consequently, the number of amateur astronomers that expressed their interest in establishing

Figure 1 – Fixed meteor stations based on CCD and/or CMOS devices operating in the framework of the Southwestern Europe Meteor Network.

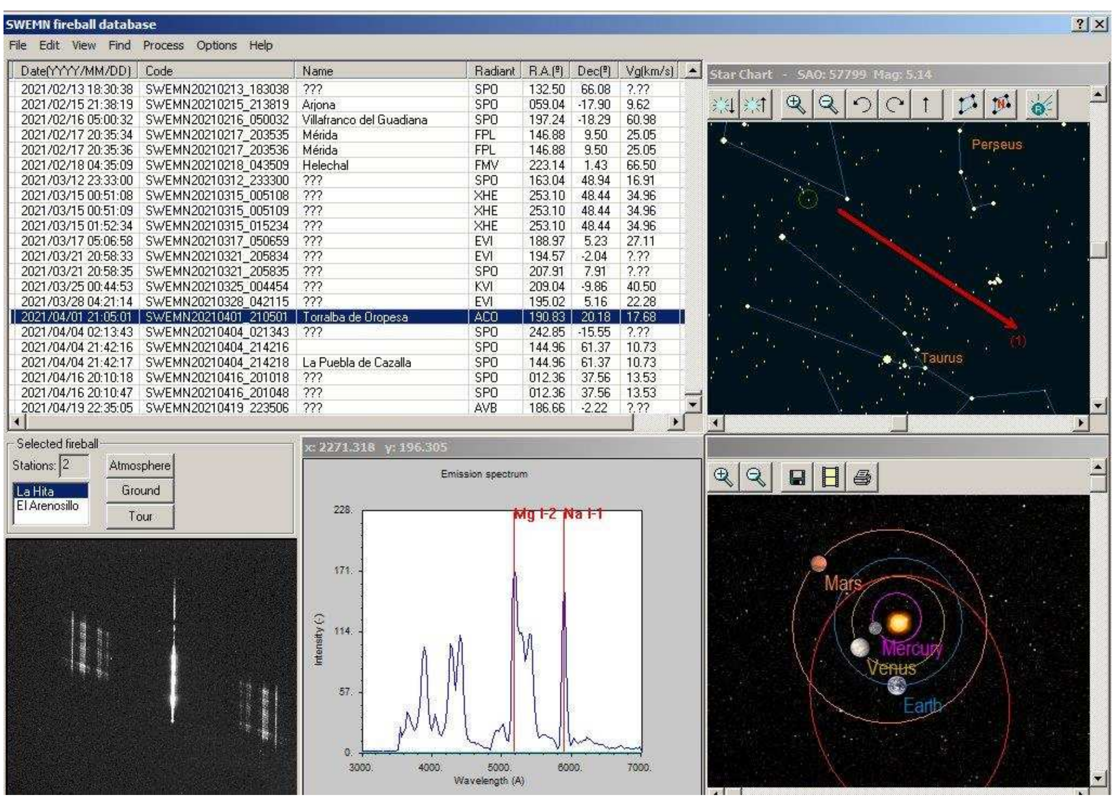

Figure 2 – Screenshot of the software interface employed by the SWEMN digital database. In this example, the interface displays the orbit viewer, the spectrum viewer, the fireball viewer and the star chart viewer.

some kind of collaboration with SMART also increased. For this reason, we decided in 2021 to convert SMART into a Pro-Am project. As a result, the number of meteor-observing stations working in the framework of the SWEMN has also increased. *Figure 1* shows an updated map of the fixed stations in this network based on CCD and/or CMOS cameras. In addition to these, there are 3 mobile video stations, and also three forward-scatter stations. One of these stations for radio meteors is mobile, and the other two operate at fixed position at La Hita and Sevilla, respectively. The video station at Coruña and Tudela are currently being setup. The systems at Coruña will begin to collect data on June 30, in commemoration of the International Asteroid Day.

3 The SWEMN digital database

One important step taken in the framework of SWEMN has been the development of a digital and interactive database containing meteors recorded and analyzed by the SMART project since this survey was started in 2006. This includes a new dedicated software to handle and exploit the contents of this database. Before these tools were available, we employed a Microsoft Excel file as a simple database to store information about meteors recorded by our cameras. Thus, every meteor spotted by SMART was assigned a unique code after its recording date and time. And then a new record was appended to that Excel file, which included that unique code and very basic data about said meteor (typically, its radiant position, radiant name, and peak magnitude). But this system was not comfortable, since in order to recover additional information for a given meteor (e.g., its emission spectrum or its lightcurve, or even the method(s) employed to perform the calculations), the operator had to locate those data manually in the specific storage device where the all of the files recorded and calculated for that particular event were stored. This manual process was very slow, and did not allow to perform automatic or efficient comparisons between the different events included in the Excel file.

The new database is the first digital database ever developed for meteors recorded over the Iberian Peninsula and neighboring areas, and it stores very comprehensive information about these events. Thus, among other data, for each meteor it contains the images taken from different observing stations, the calculated atmospheric trajectory (including geographical coordinates, velocity, and deceleration along the meteor path), the radiant coordinates, the orbital parameters of the meteoroid, the meteor lightcurve, its flickering frequency, the emission spectrum, and the main physical properties of the meteoroid (bulk density, diameter, initial and terminal mass, and strength).

Each event is also identified in the SWEMN database by means of its unique code. And, in addition to the above-mentioned results obtained from the analysis of each meteor, this database also stores the *x*, *y* coordinates for the meteor and reference stars on each image recorded for the event, information about the method(s) and software package(s) employed to obtain the different parameters calculated for the meteor, the name of the operator(s) involved in the recording and analysis of the event, and even the reports (if any) provided by causal eyewitness.

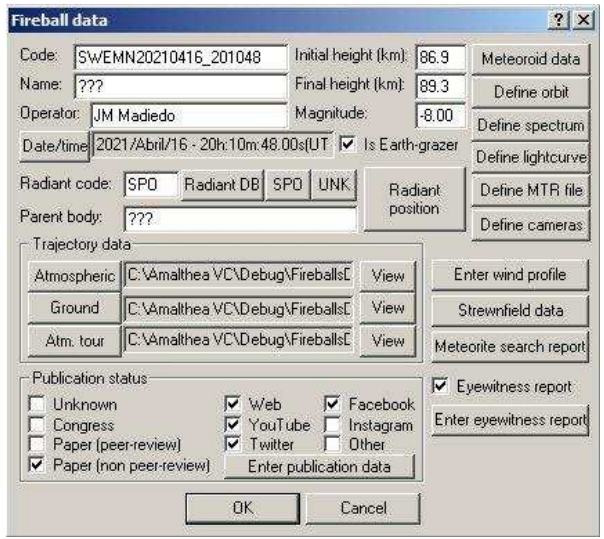

Figure 3 – Screenshot of the software interface that allows to define manually a new entry in the database, or modify the information related to a previously stored entry.

Software interface

The SWEMN database is stored in a binary file which is handled by a software tool developed to access, edit or enter information about meteor events. *Figure 2* shows a typical screenshot of the software interface of the digital database. This software is written in C++ and runs under MS-Windows. This interface is customizable and displays a list containing the meteor events included in the database. It provides an orbit viewer and an emission spectrum viewer. It can also display different plots, as for instance the lightcurve of the event and curves showing the evolution with time and/or height of different meteor parameters (velocity, deceleration, position, etc.) An interactive star chart displays the apparent position of the selected meteor from the different meteor-observing stations that spotted the event. This interface is connected with Google Earth, which allows viewing meteor trajectories by employing this popular software tool.

New meteor events can be added to the database either manually or automatically. *Figure 3* shows a screenshot of the software interface that allows to define manually a new entry in the database, or modify the information related to a previously stored entry. The automatic option scans disk drives or folders specified by the user and locates output files produced by our meteor analysis software packages. These files contain the results from the calculations related to a specific meteor (e.g., spectrum, lightcurve, orbital data, atmospheric path, etc.). If the software finds in those files a meteor that was not previously stored in the database, then it includes it automatically. After this automatic process takes place, new meteors appended to the database have to be validated to ensure that the corresponding information is reliable. Currently, the SWEMN database contains around 4000 validated events, most of which are fireballs with peak luminosity above mag. –7. This figure is expected to increase very rapidly as soon as the validation process advances and fainter events are also included.

Searching the database

Figure 4 shows a screenshot of the software module employed to browse information in the database. Once the user specifies the selected options, the software retrieves a list of meteor events fulfilling the search criteria. That list is displayed by a software interface identical to the one shown in *Figure 2*. In this way, the user can easily access any data or information stored in the database for a particular event contained in that list.

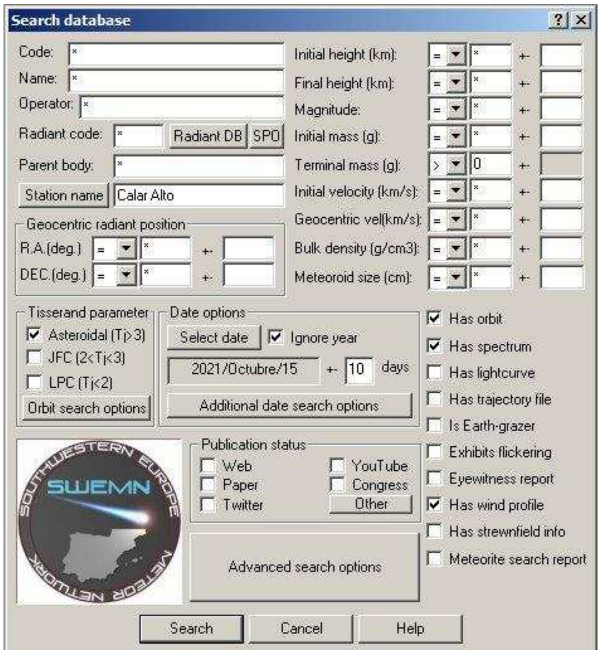

Figure 4 – Screenshot of the software interface employed to search information in the SWEMN database.

Contribution to Meteor Science

It is possible to find likely links between events included in the SWEMN database by means of the above-described software. This can be done either manually or automatically. Thus, every time a new event is appended, the software tries to find any connection with other meteors in the database. This can be very useful for different purposes. For instance, this can be employed to identify new meteor showers, or to provide valuable information about poorly-known meteoroid streams, fireball streams. Other interesting applications are related to the identification of fireball streams, especially those that could be associated with meteorite-producing events or with bright lunar impact flashes.

4 Instrumentation and methods

Below we present the main bolides recorded by our meteor-observing stations along April 2021. These bright meteors were recorded by means of analog CCD video cameras manufactured by Watec. (models 902H and 902H2 Ultimate). Their field of view ranges from 62×50 degrees to 14×11 degrees. To record meteor spectra, we have attached holographic diffraction gratings (1000 lines/mm) to the lens of some of these cameras. We have also employed digital CMOS color cameras (models Sony A7S and A7SII) operating in HD video mode (1920×1080 pixels). These cover a field of view of around 90×40 degrees. A detailed description of this hardware and the way it operates was given in previous works (Madiedo, 2017).

The atmospheric path and radiant of meteors, and also the orbit of their parent meteoroids, were obtained with the Amalthea software, developed by J.M. Madiedo (Madiedo, 2014). This program employs the planes-intersection method (Ceplecha, 1987). However, for Earth-grazing events atmospheric trajectories are obtained by Amalthea by means of a modification of this classical method (Madiedo et al., 2016). Emission spectra were analyzed with the CHIMET software (Madiedo, 2015a).

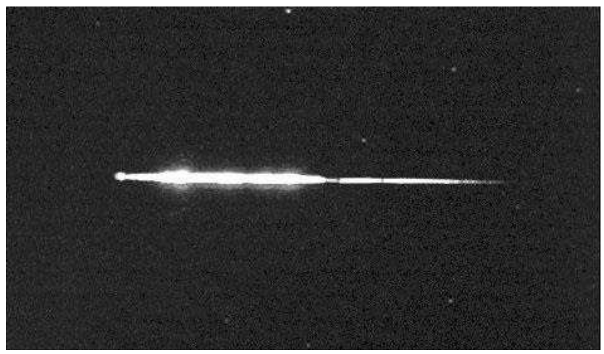

Figure 5 – Stacked image of SWEMN20210401_210501 "Torralba de Oropesa" fireball as recorded from the SWEMN meteor-observing station at La Hita Astronomical Observatory.

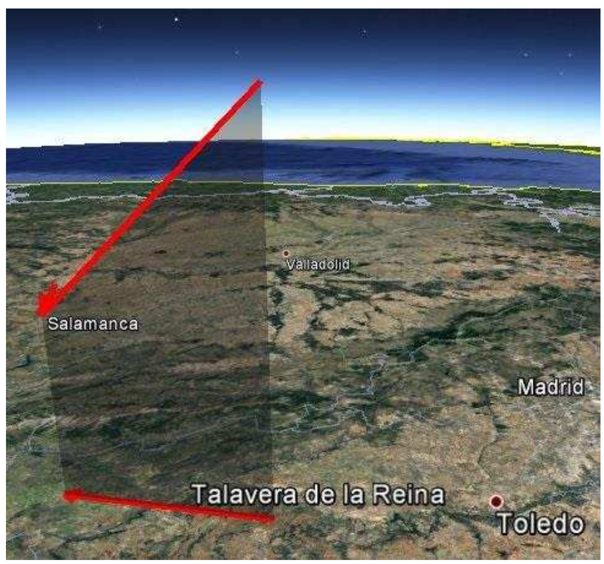

Figure 6 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210401_210501 fireball.

5 The 2021 April 1 meteor event

On April 1, our systems recorded the first bright meteor of that month. The event was spotted at $21^h05^m01.7 \pm 0.1^s$ UTC from the SWEMN stations operating at La Hita, La Sagra, Madrid, Sevilla, Calar Alto, and El Arenosillo. It had a peak absolute magnitude of –11 ± 1 (*Figure 5*). This event was included in our meteor database with the code

SWEMN20210401_210501. A video showing images of the fireball and its trajectory was uploaded to YouTube [8].

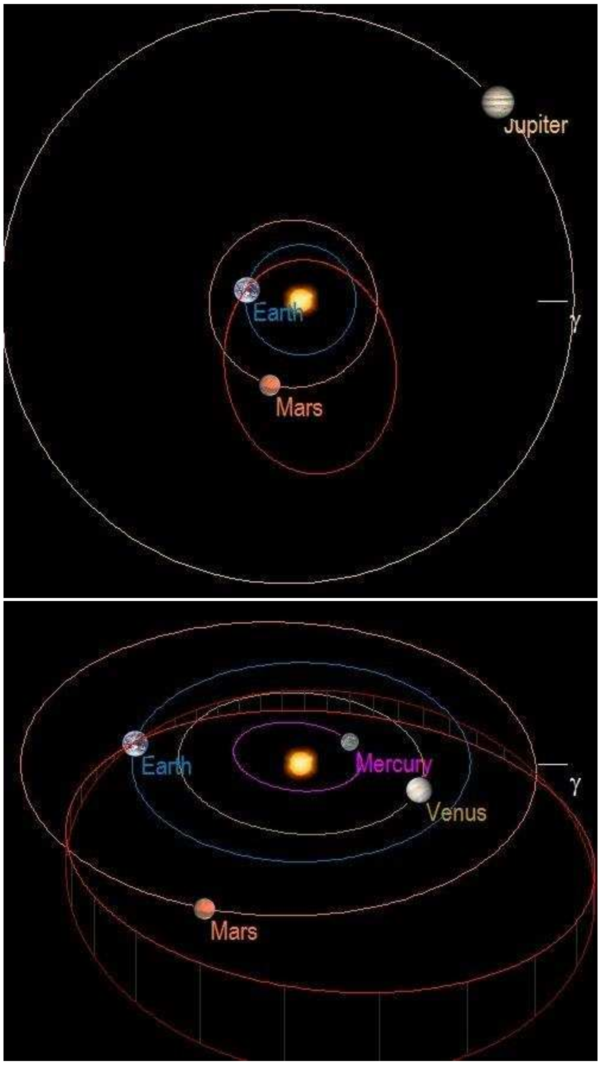

Figure 7 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210401_210501 fireball, and projection of this orbit (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

Table 1 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210401_210501 "Torralba de Oropesa" fireball.

a (AU)	1.98 ± 0.07	*ω* (º)	249.6 ± 0.2
e	0.62 ± 0.01	Ω (º)	12.06187 ± 10-5
q (AU)	0.749 ± 0.002	*i* (º)	11.5 ± 0.2

Atmospheric trajectory, radiant and orbit

By combining the recordings from the different stations that observed this fireball, we concluded that this bright meteor overflew the province of Toledo. Besides, we obtained a pre-atmospheric velocity for the progenitor meteoroid of $v_\infty = 21.1 \pm 0.3$ km/s, with the position of the apparent radiant at the equatorial coordinates $\alpha = 190.82^o$, $\delta = +20.18^o$. The analysis of the atmospheric path also revealed that the meteor began at a height $H_b = 92.0 \pm 0.5$ km, and ended at an altitude $H_e = 43.3 \pm 0.4$ km. The zenith angle of this trajectory was of about 45 degrees. Since the terminal point of the bolide was almost over the vertical of the town of Torralba de Oropesa, we named the fireball after this location. The atmospheric path of the meteor and its projection on the ground are shown in *Figure 6*.

The geocentric velocity of the meteoroid was $v_g = 17.6 \pm 0.3$ km/s. Its orbital parameters before its encounter with our planet are shown in *Table 1*, and this orbit is drawn in *Figure 7*. The information found in the IAU meteor database indicates that the fireball was an April α-Comae Berenicids (ACO#0272). This poorly-known meteoroid stream produces every year a display of meteors peaking around April 7 (Porubcan and Gavajdova, 1994). According to the calculated value of the Tisserand parameter with respect to Jupiter ($T_J = 3.57$), the meteoroid followed an asteroidal orbit before impacting the Earth's atmosphere. This agrees with the proposed asteroidal origin for this stream.

Emission spectrum

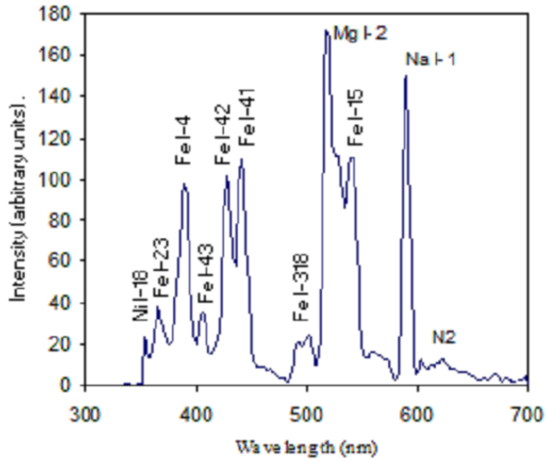

Figure 8 – Calibrated emission spectrum of the SWEMN20210401_210501 "Torralba de Oropesa" fireball.

The emission spectrum of the SWEMN20210401_210501 fireball was recorded by our spectrographs from the astronomical observatories of Calar Alto, La Hita, La Sagra, and El Arenosillo. As in previous works, this spectrum was analyzed with the ChiMet software, which calibrates the signal in wavelength and then corrects it by taking into account the spectral sensitivity of the device (Madiedo et al., 2014; Madiedo, 2015b; Passas et al., 2016). The resulting calibrated spectrum is shown in *Figure 8*, where the most remarkable emission lines have been highlighted. The majority of these correspond to neutral iron, as usual in meteor spectra (Borovička, 1993; Madiedo, 2014; Espartero and Madiedo, 2016). Thus, we have identified the emissions from Fe I-23, Fe I-4, Fe I-43, Fe I-42, Fe I-41, Fe I-318, and Fe I-15. Nevertheless, the most important emissions are those of the Na I-1 doublet (588.9 nm) and the Mg I-2 triplet (516.7 nm). The Ni-18 line was also

[8] https://youtu.be/daEYX6agr-k

detected, and the contribution from atmospheric N2 is present in the red part of the spectrum.

6 The 2021 April 4 fireball

This bolide was recorded from the SWEMN meteor-observing stations operating at La Sagra, La Hita, Madrid, Sevilla, and El Arenosillo. The fireball can be viewed on this YouTube video[9], and had a peak absolute magnitude of –9 ± 1 (*Figure 9*). It appeared at $21^h42^m18.4 \pm 0.1^s$ UTC, and so it was included in our database under the code SWEMN20210404_214218.

Atmospheric path, radiant and orbit

This fireball overflew the provinces of Sevilla and Cadiz (west of Andalusia). The meteoroid hit the atmosphere with an initial velocity v_∞ = 15.4 ± 0.3 km/s, and the apparent radiant of the meteor was located at the equatorial coordinates α = 144.9º, δ = +61.4º. The bolide began at an altitude H_b = 81.0 ± 0.5 km, near from the vertical of the town of La Puebla de Cazalla (province of Sevilla). In our meteor database we named the event after this location. The terminal point of its trajectory was reached at a height H_e = 29.8 ± 0.5 km over the northeast of the province of Cadiz. The calculated atmospheric path and its projection on the ground are shown in *Figure 10*.

Figure 9 – Stacked image of the SWEMN20210404_214218 "La Puebla de Cazalla" fireball as recorded from the SWEMN meteor-observing station located at El Arenosillo.

Table 2 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210404_214218 fireball.

a (AU)	2.7 ± 0.2	*ω* (º)	183.0 ± 0.2
e	0.63 ± 0.03	Ω (º)	15.04381 ± 10^{-5}
q (AU)	0.9997 ± 0.0001	*i* (º)	11.5 ± 0.3

Figure 10 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210404_214218 fireball.

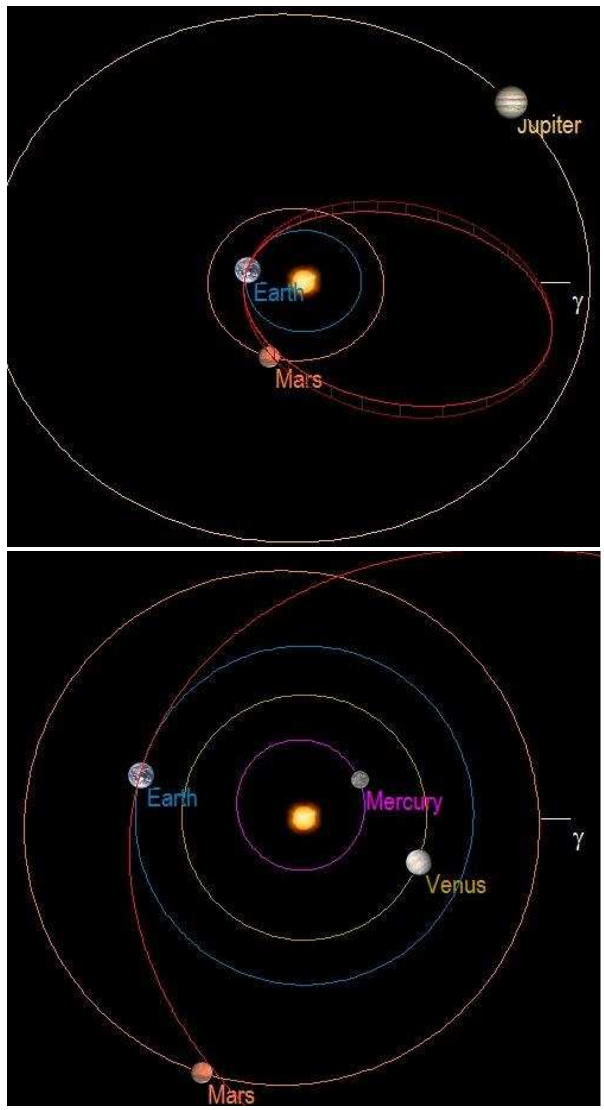

Figure 11 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210404_214218 fireball, and projection of this orbit (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

[9] https://youtu.be/XpYAGNiRkEQ

The calculation of the orbital elements of the progenitor meteoroid yields the results listed in *Table 2*, and the corresponding heliocentric orbit is shown in *Figure 11*. The value derived for the geocentric velocity is v_g = 10.7 ± 0.4 km/s. The value of the Tisserand parameter with respect to Jupiter (T_J = 3.0) shows that the orbit followed by this meteoroid would lie in the limit between an asteroidal orbit and a Jupiter Family Comet (JFC) orbit. Radiant and orbital data do not match any of the meteoroid streams listed in the IAU meteor database. So, we concluded that this event was produced by the sporadic background.

7 The 2021 April 16 fireball

At $20^h10^m14.8 \pm 0.1^s$ UTC on April 16, we recorded a slow bolide with a peak absolute magnitude of –8 ± 1. This was an Earth-grazing fireball that was spotted from the meteor-observing stations located at La Hita, Sevilla, El Arenosillo, La Sagra, and Madrid (*Figure 12*). It could be also seen by many casual eyewitnesses, and most of them reported that the bolide exhibited a reddish color. A video showing this event was uploaded to YouTube[10]. It was included in the SWEMN meteor database with the code SWEMN20210416_201014.

Atmospheric path, radiant and orbit

The luminous phase of this event began over the northwest of Spain and ended over the southeast of this country. The projection on the ground of the atmospheric trajectory of the fireball is shown in *Figure 13*. From the preliminary analysis of this trajectory, we obtained that the apparent radiant was located at the equatorial coordinates α = 12.3º, δ = +37.5º. The meteoroid hit the atmosphere over the province of Lugo (Galicia), with an initial velocity v_∞ = 16.1 ± 0.2 km/s. The initial and terminal points of this path were located at an altitude H_b = 86.9 ± 0.5 km and H_e = 89.3 ± 0.5 km, respectively. At this final stage the fireball was located over the Mediterranean Sea, next to the coast of Almería (Andalusia).

Figure 12 – Stacked image of the SWEMN20210416_201014 fireball as recorded from La Hita Observatory.

Figure 13 – Projection on the ground of the trajectory of the SWEMN20210416_201014 Earth-grazing fireball.

The heliocentric orbit of the meteoroid before its encounter with our planet is drawn in *Figure 14*, and the value of the corresponding orbital parameters are listed in *Table 3*. For the geocentric velocity we have obtained the value v_g = 11.9 ± 0.2 km/s. and the Tisserand parameter with respect to Jupiter yields T_J = 6.19. According to this, the meteoroid followed an asteroidal orbit before entering the atmosphere. As in the previous case, and according to the information found in the IAU meteor database, we associated this event with the sporadic background.

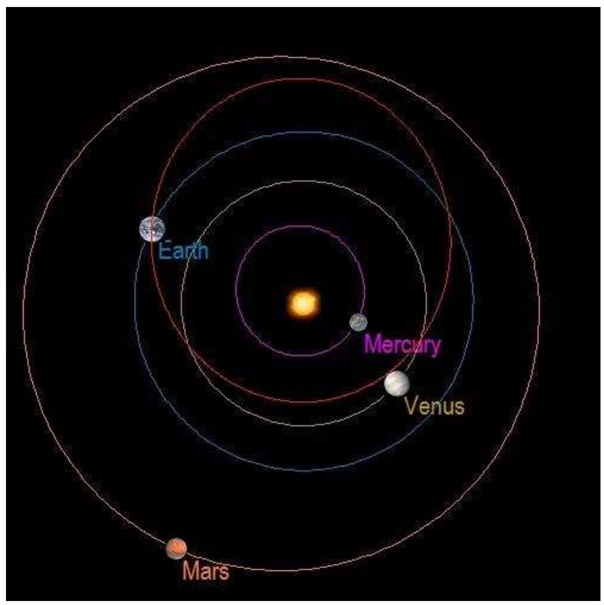

Figure 14 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20210416_201014 fireball before the encounter of this particle with our planet.

It is interesting that the meteoroid exhibited a non-zero terminal mass. So, the surviving fragment left the atmosphere following a modified orbit. A paper describing

[10] https://youtu.be/lofMkg8a7wQ

in detail the circumstances of this case is currently in preparation.

Table 3 – Orbital parameters (J2000) of the progenitor meteoroid of the SWEMN20210416_201014 fireball before the encounter of this particle with our planet.

a (AU)	0.96 ± 0.01	ω (º)	61.2 ± 1.0
e	0.393 ± 0.005	Ω (º)	26.75338 ± 10^{-5}
q (AU)	0.5836 ± 0.0002	*i* (º)	7.6 ± 0.3

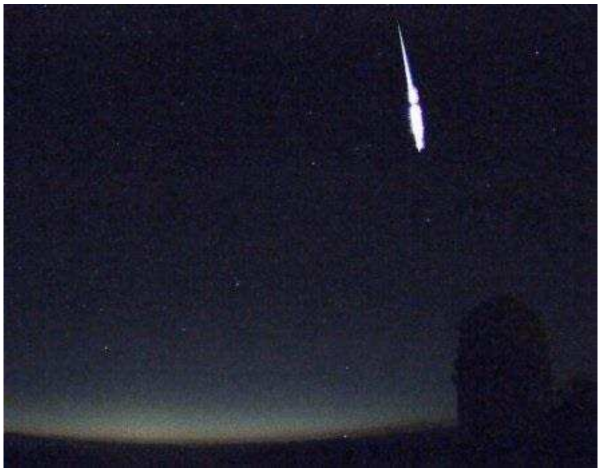

Figure 15 – Stacked image of the SWEMN20210423_040329 fireball as recorded from Calar Alto.

8 The 2021 April 23 fireball

This bolide was recorded at $4^h03^m29.0 \pm 0.1^s$ UTC on 2021 April 23 from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, and Sierra Nevada. It reached a peak absolute magnitude of –9 ± 1 (*Figure 15*). A video about this fireball was uploaded to YouTube[11]. The meteor was included in the SWEMN meteor database with the code SWEMN20210423_040329.

Atmospheric path, radiant and orbit

According to our calculations, the meteoroid entered the atmosphere with an initial velocity $v_\infty = 47.6 \pm 0.4$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 274.9$º, $\delta = +34.0$º. The event overflew the Mediterranean Sea. It began at an altitude $H_b = 114.2 \pm 0.5$ km, and ended at a height $H_e = 59.7 \pm 0.5$ km over the sea. This atmospheric trajectory and its projection on the ground are shown in *Figure 16*.

Table 4 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210423_040329 fireball.

a (AU)	11.2 ± 3.7	ω (º)	211.6 ± 0.4
e	0.91 ± 0.02	Ω (º)	32.94233 ± 10^{-5}
q (AU)	0.9338 ± 0.0009	*i* (º)	79.3 ± 0.3

Figure 16 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210423_040329 fireball.

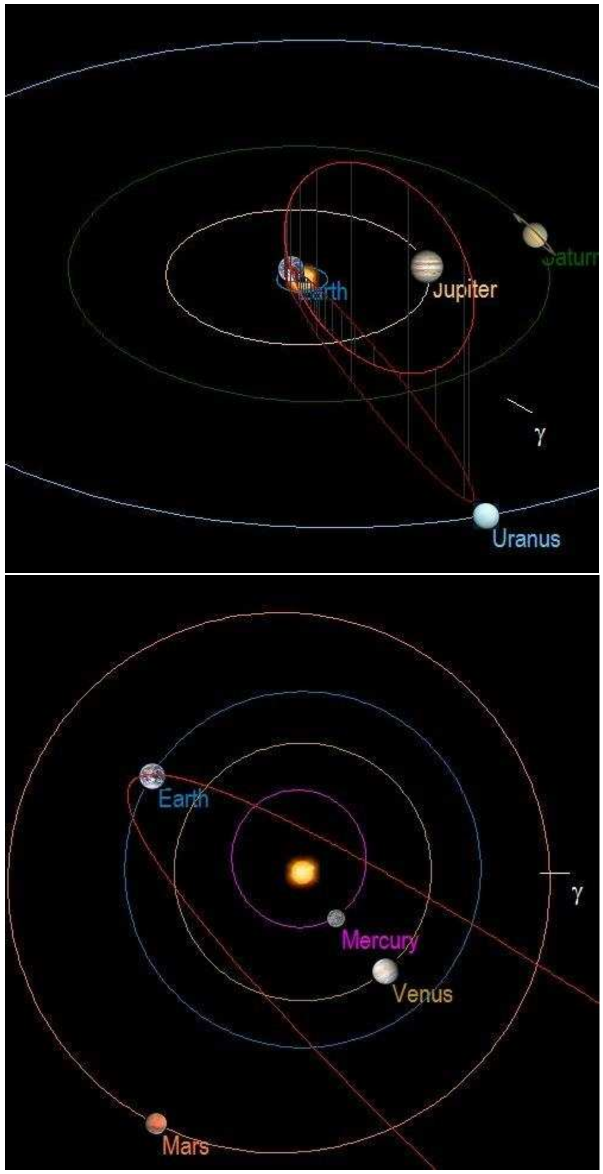

Figure 17 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210423_040329 fireball, and its projection (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

[11] https://youtu.be/wGkKYSHOhXY

Table 4 contains the orbital elements calculated for the parent meteoroid. This orbit is plotted in *Figure 17*. The calculated value of the geocentric velocity of this particle is v_g = 46.2 ± 0.4 km/s. The Tisserand parameter with respect to Jupiter yields T_J = 0.6, which shows that this meteoroid followed a cometary orbit before entering our atmosphere. In fact, according to the information found in the IAU meteor database, these results show that the fireball was an April Lyrid (LYR#0006). This major meteor shower, which is produced by meteoroids from Comet C/1861 G1 (Thatcher), reaches its activity peak around April 22 (Jenniskens et al., 2016). So, this event was recorded a few hours after said peak.

Emission spectrum

Our spectrographs located at the astronomical observatories of Sierra Nevada and Calar Alto recorded the emission spectrum of this Lyrid fireball. *Figure 18* shows the calibrated signal, together with the most important emissions. As can be noticed, the most important emission line is that from Fe I-4. Additional contributions from neutral iron have been also found, and the most significant ones are those from Fe I-23, Fe I-21, Fe I-43, Fe I-41, Fe I-318, and Fe I-15. The lines produced by Mg I-2 and Na I-1 are also present.

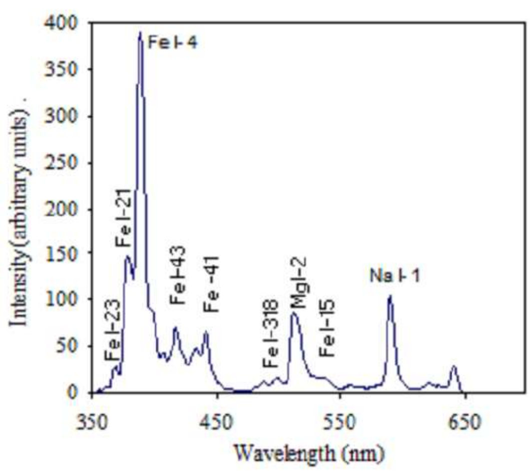

Figure 18 – Calibrated emission spectrum of the SWEMN20210423_040329 fireball.

9 Conclusion

We have focused here two new steps taken in the framework of SWEMN. The first of these is our openness to the amateur astronomy community. The second involves the development of the first digital database containing information about bolides and meteors recorded over the Iberian Peninsula and neighboring areas, and the software tools necessary to handle this new resource. We have described the main characteristics of this new tool and its likely contribution to, for instance, the identification of new meteor showers and fireball streams.

We have also presented the most remarkable fireballs recorded in April 2021 by the Southwestern Europe Meteor Network. The absolute magnitude of these events during their peak luminosity ranged from –8 to –11. The first of these is the "Torralba de Oropesa" mag. –11 bolide, which was recorded on April 1 and overflew the province of Toledo. This fireball was associated with the April α-Comae Berenicids (ACO#0272), a poorly-known meteoroid stream that peaks around April 7. Our results are consistent with the proposed asteroidal origin for this stream. In the spectrum obtained for this event the most important lines are those of Na I-1 (588.9 nm) and Mg I-2 (516.7 nm). The signal also exhibits the emission from several neutral iron multiplets (Fe I-23, Fe I-4, Fe I-43, Fe I-42, Fe I-41, Fe I-318, and Fe I-15) and the Ni I-18 line.

The "La Puebla de Cazalla" event, spotted on April 4, overflew the provinces of Sevilla and Cádiz (Andalusia) and reached a peak absolute magnitude of –9. The parent meteoroid followed a JFC orbit and was associated with the sporadic background.

An Earth-grazing fireball with a peak absolute magnitude of –8 was observed on April 16. It overflew Spain from northwest to southeast, and ended over the Mediterranean Sea. The meteoroid, which followed and asteroidal orbit before its encounter with our planet, was also associated with the sporadic background and exhibited a non-zero terminal mass. So, it left the atmosphere with a modified orbit.

And finally, we spotted a mag. –9 Lyrid that overflew the Mediterranean Sea on April 23, some hours after the peak of this major shower. The most remarkable contributions in its emission spectrum are those produced by Fe I-4, Fe I-21, Mg I-2, and Na I-1. An in-deep analysis of this spectrum will provide key information about the composition of Lyrid meteoroids.

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