The Southwestern Europe Meteor Network: new advances and analysis of bright fireballs recorded from September to December 2021

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In this work we focus on some recent improvements performed in the framework of the Southwestern Europe Meteor Network (SWEMN) and the SMART project. Thus, by employing artificial intelligence methods, we have significantly enhanced the capabilities of our fireball database to automatically disseminate its most remarkable contents through social networks and other channels. This is the first digital database dedicated to meteor events recorded over Spain and neighboring areas. In addition, we have expanded our network by deploying new meteor cameras. We also present in this work the most relevant fireballs recorded by SWEMN from September to December 2021, including the emission spectrum of some of these events.

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., 2015a, b). A strong synergy has been proved to exist between this survey and the SMART project (Madiedo et al., 2015a, b).

This work focuses on a series of advances performed in the framework of SWEMN along the end of last year and January 2022. The most important of these is related to the use of artificial intelligence methods to disseminate among the general public information about fireball events recorded by our meteor network. To do this, we employ as essential tools the SWEMN digital database containing information about bolides and meteors recorded over the Iberian Peninsula, but also our SAMIA software. Other advances have to do with the expansion of the SWEMN network. On the other hand, this work also presents some of the most remarkable fireballs recorded by our systems from September to December 2021.

2 New capabilities of the SWEMN digital database: use of artificial intelligence (AI) for dissemination in social networks and media

The SMART survey is currently co-funded by the Spanish Ministry for Science and Innovation. One of the objectives of this project is related to the dissemination of our scientific results among the general public. For this purpose, we employ several strategies. Thus, we disseminate this information through social networks (mainly Twitter and Facebook), information media, our website, and also YouTube. Thus, since the SMART project was started in

2006 the results obtained in the framework of this survey and the most remarkable fireballs recorded by our meteor stations have been widely disseminated 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 some kind of collaboration with SMART also increased. The time consumed by this dissemination process was very significant, since all of the information necessary for this purpose was gathered manually, and the corresponding reports were also prepared by hand.

One important step taken in the framework of SWEMN along 2021 was the development of the first digital and interactive database containing meteors recorded and analyzed by the SMART project since this survey was started in 2006. This step included the development of a new dedicated software (the SAMIA software) to handle and exploit the contents of this database (Madiedo et al., 2021). AI methods were included in SAMIA to automatically derive valuable information from the events included in that database. And recently, those methods have been expanded to automatically perform most of the above-mentioned dissemination of information among the general public on social networks and media. This has two main advantages: first, it saves very valuable time to our team. And second, the information is disseminated much faster.

In relation to social networks, the first task that SAMIA could perform in this context was the automatic update of our website. More specifically, of the webpage containing information about the most relevant fireballs recorded and analyzed in the framework of the SMART project. In that way, the program adds for each new bolide a short description of the event, a stacked photo of the fireball as recorded from a given meteor station, and also a link to the video uploaded to YouTube explaining the main circumstances of the bolide. To do this, SAMIA edits the HTML code of the webpage dedicated to these fireballs, and once the new information is appended to that HTML page, the software automatically uploads the updated file to the server where the page is hosted. Besides, the AI in the SAMIA software also writes automatically Twitter threads describing the circumstances of a particular event. And it also writes the text necessary to inform about the same event on Facebook. By following this procedure, the information can be easily disseminated on both social networks. Currently, the text for Twitter and Facebook is written in Spanish only. But SAMIA also writes automatically text to describe the event on the YouTube channel we employ to disseminate fireball videos. In this case, the text is written in English and Spanish.

The last step taken in this automatic dissemination process consists on the preparation of press releases to inform about a particular event through the media (TV, radio, press, etc.). The use of a press release fully created by SAMIA's AI from the information contained in the SWEMN digital database was done for the first time in January 2022. Press releases are prepared by SAMIA in MS-Word DOC format, and in Spanish language. At this stage, the press release must be supervised by a human operator, who decides if the MS-Word file can be sent to the media, or if it needs some corrections before being submitted.

3 Expansion of the SWEMN network

Our meteor network went on growing during the second half of 2021 and the beginning of 2022. Thus, a new station named "El Aljarafe" started operation in October 2021. This station was setup by an amateur astronomer who joined the Pro-Am initiative that SWEMN started last year. The station was named after the area in which it was established, nearby to the city of Sevilla. It currently employs two HD CMOS cameras to monitor meteor activity during the night, but also the activity of bright fireballs during daytime.

On the other hand, we have expanded our video station in La Coruña (region of Galicia, NW of Spain). The first camera deployed there started operation on 2021 June 30, in commemoration of the International Asteroid Day. During the last week of 2021 and the first week of 2022 three additional video devices have been installed there.

It is also worth mentioning that SWEMN is planning the installation of a series of new professional meteor-observing stations along 2022. The first of these will be deployed in Mallorca, and it is expected to be fully operative along next spring. The cameras deployed at this location will significantly increase the coverage of our meteor network over the Mediterranean Sea, the south of France, and the north of Africa.

4 Instrumentation and methods

Below we present the most remarkable bright meteors recorded by our meteor-observing stations from September to December 2021. These events 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 70 × 40 degrees. A detailed description of this hardware and the way it operates was given in previous work (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, 2015).

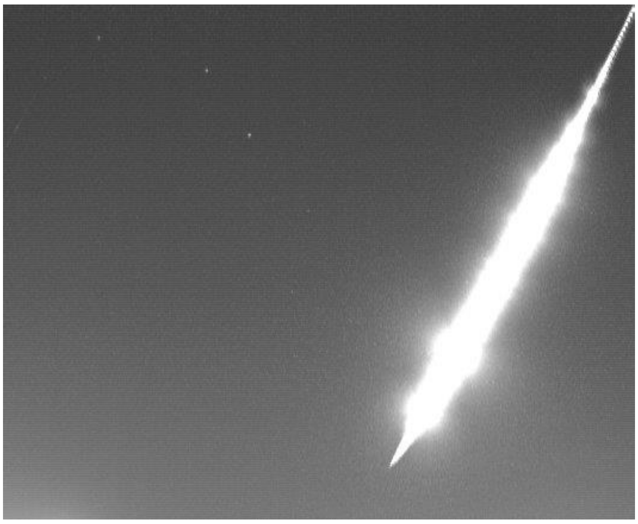

Figure 1 – Stacked image of SWEMN20210915_202553 "La Albuera" fireball as recorded from the SWEMN meteor-observing station at Sevilla.

Figure 2 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210915_202553 fireball.

5 The 2021 September 15 meteor event

On September 15, at $20^h25^m53.9 \pm 0.1^s$ UTC, our systems recorded an impressive fireball from the SWEMN meteor-observing stations operating at La Hita, La Sagra, Sierra Nevada, Sevilla, Calar Alto, and Huelva. It had a peak absolute magnitude of –12 ± 1 (*Figure 1*). This event was included in our meteor database with the code SWEMN20210915_202553. A video showing images of the fireball and its trajectory was uploaded to YouTube [28].

Table 1 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210915_202553 "La Albuera" fireball.

a (AU)	2.6 ± 0.1	ω (°)	246.62 ± 0.01
e	0.71 ± 0.01	Ω (°)	172.91443 ± 10^{-5}
q (AU)	0.753 ± 0.002	i (°)	8.0 ± 0.1

Atmospheric trajectory, radiant and orbit

By analyzing the recordings obtained from the meteor stations that observed this fireball, we found that this bright meteor overflew the province of Badajoz. 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 $\alpha = 335.5°$, $\delta = +9.4°$. The analysis of the atmospheric path also revealed that the meteor began at a height $H_b = 91.9 \pm 0.5$ km, and ended at an altitude $H_e = 22.2 \pm 0.5$ km. The zenith angle of this trajectory was of about 46 degrees. Since the terminal point of the bolide was almost over the vertical of the town of La Albuera, we named the fireball after this location. The atmospheric path of this deep-penetrating meteor and its projection on the ground are shown in *Figure 2*. The analysis of the terminal point of the atmospheric trajectory indicated that a small part of the meteoroid survived the ablation process and reached the ground as a meteorite. The derived total surviving mass, however, was very small, below 25 grams. In spite of that, an expedition was organized by the SWEMN network to the strewnfield determined from our calculations. Expeditions organized by amateurs were also organized to the same area. However, nothing was found.

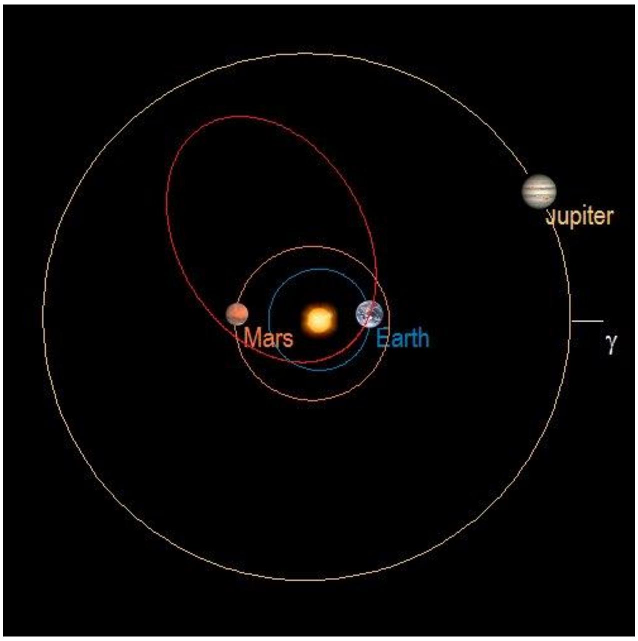

Figure 3 – Projection on the ecliptic of the orbit (red line) of the parent meteoroid of the SWEMN20210915_202553 fireball.

The geocentric velocity of the meteoroid was $v_g = 17.7 \pm 0.3$ km/s. Its orbital parameters before its encounter with our planet are shown in *Table 1*, and this orbit is drawn in *Figure 3*. Radiant and orbital data do not match any of the meteoroid streams listed in the IAU meteor database[29]. So, we concluded that this event was produced by the sporadic background. According to the calculated value of the Tisserand parameter with respect to Jupiter ($T_J = 3.0$), the meteoroid followed an asteroidal orbit before impacting the Earth's atmosphere.

[28] https://youtu.be/qyE0iNzidvE

[29] http://www.astro.amu.edu.pl/~jopek/MDC2007/

Emission spectrum

The emission spectrum of the SWEMN20210915_202553 meteor was recorded by our spectrographs from the astronomical observatories of Calar Alto and La Hita. We have analyzed it 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, 2017). The resulting calibrated spectrum is shown in *Figure 4*, where the most remarkable emission lines have been highlighted. Most of these correspond to neutral iron, as usual in meteor spectra (Borovička, 1993; Madiedo, 2014). Thus, we have identified the emissions from Fe I-4, Fe I-42, Fe I-41, Fe I-318, and Fe I-15. The most important emissions are those of the Mg I-2 triplet (516.7 nm), and the Fe I-15 multiplet around 540 nm. The emission from the Na I-1 doublet (588.9 nm) is also remarkable, and the emission from Mg I-3 was also found. In addition, the contribution from atmospheric N2 is present in the red part of the spectrum.

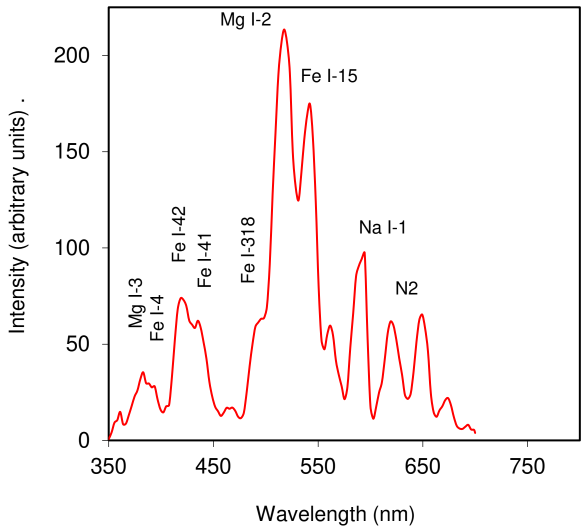

Figure 4 – Calibrated emission spectrum of the SWEMN20210915_202553 "La Albuera" fireball.

6 The 2021 October 20 fireball

This fireball was recorded from the SWEMN meteor-observing stations operating at La Sagra, La Hita, Madrid, Sevilla, Sierra Nevada, and El Guijo. The bolide can be viewed on this YouTube video[30]. It had a peak absolute magnitude of –9 ± 1 (*Figure 5*). It appeared at $23^h16^m07.1 \pm 0.1^s$ UTC, and so it was included in our database under the code SWEMN20211020_231607.

Atmospheric path, radiant and orbit

This fireball overflew the provinces of Segovia, Valladolid, and Avila (northwest of Spain). The meteoroid hit the atmosphere with an initial velocity $v_\infty = 66.2 \pm 0.4$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 94.0°$, $\delta = +32.0°$. The bolide began at an altitude $H_b = 135.1 \pm 0.5$ km over the northeast of the province of Segovia. The terminal point of its trajectory was reached at a height $H_e = 73.7 \pm 0.5$ km over the north of the province of Avila, near the vertical of the town of Madrigal de las Altas Torres. In our meteor database we named the event after this location. The calculated atmospheric path and its projection on the ground are shown in *Figure 6*.

Figure 5 – Stacked image of the SWEMN20211020_231607 "Madrigal de las Altas Torres" fireball as recorded from the SWEMN meteor-observing station located at La Hita.

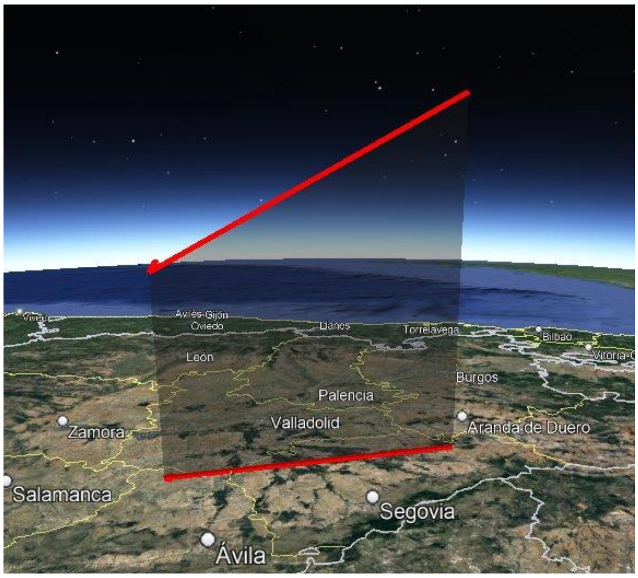

Figure 6 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20211020_231607 fireball.

Table 2 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20211020_231607 fireball.

a (AU)	5.8 ± 1.1	ω (°)	268 ± 1
e	0.90 ± 0.01	Ω (°)	207.48371 ± 10^{-5}
q (AU)	0.538 ± 0.008	i (°)	161.4 ± 0.1

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 7*. The value derived for the geocentric velocity is $v_g = 64.9 \pm 0.4$ km/s. The value of the Tisserand parameter with respect to Jupiter ($T_J = 0.05$) shows that the meteoroid followed a

[30] https://youtu.be/Uq-TszJLnLY

cometary orbit. Calculated radiant and orbital data show that the meteoroid was associated with the κ-Aurigids (KAU#0537), according to the information listed in the IAU meteor database. The proposed parent body for this minor and poorly-known meteoroid stream is Comet C/1957U1(Latyshev-Wild-Burnham) (Šegon et al., 2014).

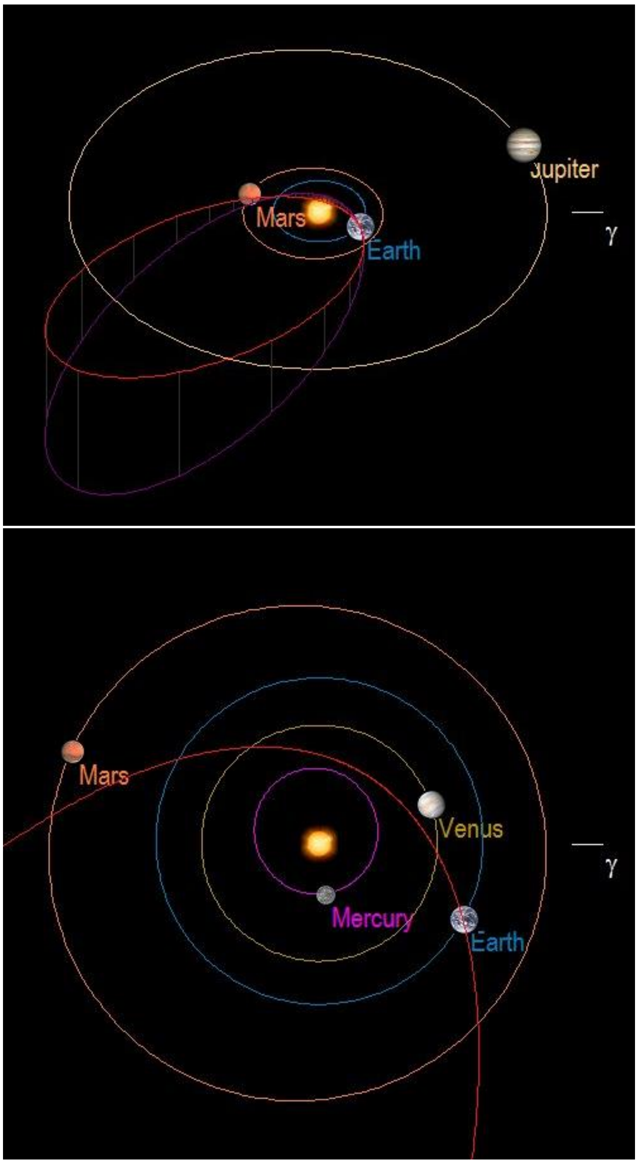

Figure 7 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210404_214218 fireball, and projection of this orbit (violet line) on the ecliptic plane; Down: close-up view of the orbit.

7 The 2021 November 12 fireball

At $0^h34^m48.0 \pm 0.1^s$ UTC on November 12, we recorded a deep-penetrating bolide with a peak absolute magnitude of –13 ± 1 (*Figure 8*). The event was spotted from the meteor-observing stations located at El Guijo, Sierra Nevada, La Hita, and Sevilla. It was included in the SWEMN meteor database with the code SWEMN20211112_003448.

Atmospheric path, radiant and orbit

The analysis of the atmospheric trajectory of the event reveals that the luminous phase started at an altitude $H_b = 96.7 \pm 0.4$ km over the east of the province of Salamanca. The meteoroid stroke the atmosphere with a velocity v_∞ of about 28.5 km/s. The apparent radiant was located at the equatorial coordinates $\alpha = 55.6°$, $\delta = +16.5°$. The bolide penetrated the atmosphere till a final height $H_e = 25.0 \pm 0.4$ km over the same province.

Figure 8 – Stacked image of the SWEMN20211112_003448 fireball as recorded from El Guijo Observatory.

Figure 9 – Projection on the ground of the trajectory of the SWEMN20211112_003448 fireball.

The projection on the ground of the atmospheric trajectory is shown in *Figure 9*. The parameters of the heliocentric orbit (*Figure 10*) followed by the meteoroid before its encounter with our planet are shown in *Table 3*. These data confirmed the association of the event with the Southern Taurid meteoroid stream (STA#0002).

The analysis of the lightcurve reveals that the fireball exhibited several flares along its path in the atmosphere. These flares took place as a consequence of the sudden disruption of the progenitor meteoroid when the aerodynamic pressure exceeded the tensile strength of the particle. From the analysis of these breakups we estimated that the tensile strength of the meteoroid was of about $(2.4 \pm 0.5)\cdot 10^7$ dyn/cm^2.

Our calculations also reveal that the meteoroid was not completely ablated in the atmosphere, since at the terminal point of the luminous trajectory a mass of about 20 g survived the ablation process. The dark flight was also analyzed and the landing area of the surviving mass was determined. An expedition was organized to that area, where experts in meteorite recovery participated in collaboration with SWEMN. Unfortunately, part of the predicted landing area had just been plowed, and the meteorite was not found.

Table 3 – Orbital parameters (J2000) of the progenitor meteoroid of the SWEMN20211112_003448.

a (AU)	2.6 ± 0.1	*ω* (º)	101.6 ± 0.1
e	0.82 ± 0.01	Ω (º)	49.51242 ± 10^{-5}
q (AU)	0.455 ± 0.004	*i* (º)	3.7 ± 0.1

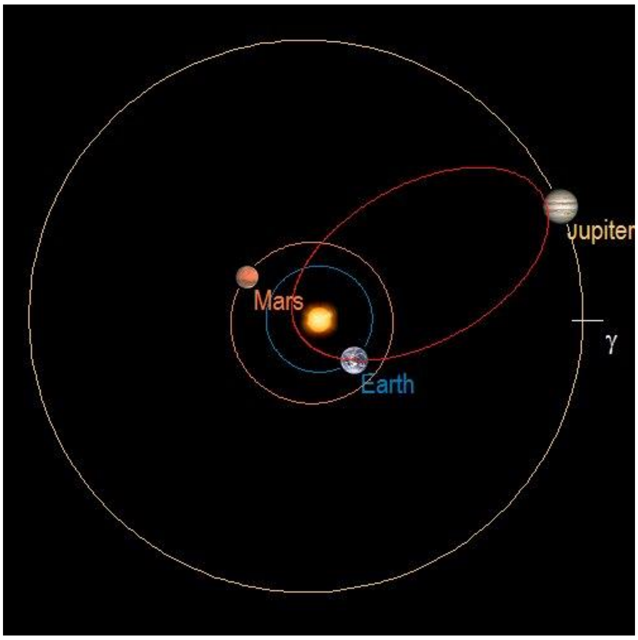

Figure 10 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20211112_003448 fireball.

8 The 2021 November 28 fireball

This bolide was recorded at 22h39m04.4 ± 0.1s UTC on 2021 November 28 from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, Huelva, and Sierra Nevada. It reached a peak absolute magnitude of –12 ± 1 (*Figure 11*). A video about this fireball was uploaded to YouTube[31]. The meteor was included in the SWEMN meteor database with the code SWEMN20211128_223903.

Atmospheric path, radiant and orbit

According to our calculations, the meteoroid entered the atmosphere with an initial velocity $v_\infty = 20.1 \pm 0.3$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 16.8°$, $\delta = +57.9°$. The event overflew the Atlantic Ocean. It began at an altitude $H_b = 89.7 \pm 0.4$ km, and ended at a height $H_e = 45.7 \pm 0.4$ km over the sea. This atmospheric trajectory and its projection on the ground are shown in *Figure 12*.

Figure 11 – Stacked image of the SWEMN20211128_223903 fireball as recorded from Sevilla.

Table 4 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20211128_223903 fireball.

a (AU)	3.1 ± 0.2	*ω* (º)	216.6 ± 0.1
e	0.71 ± 0.01	Ω (º)	246.63159 ± 10^{-5}
q (AU)	0.904 ± 0.001	*i* (º)	19.5 ± 0.3

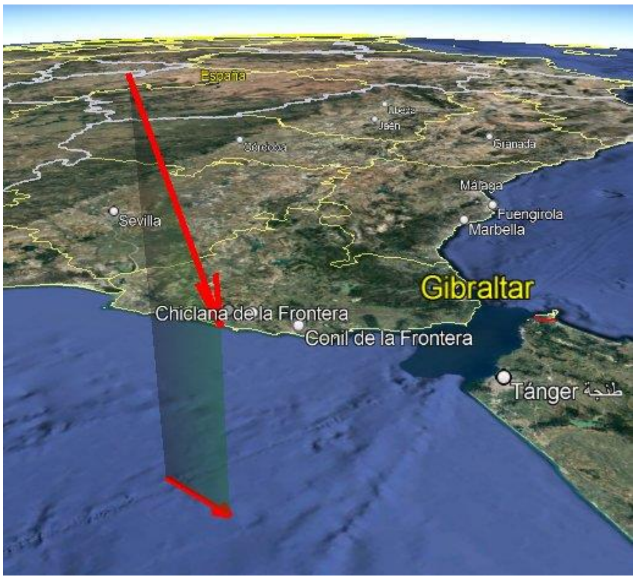

Figure 12 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20211128_223903 fireball.

Table 4 contains the orbital elements calculated for the parent meteoroid. This orbit is plotted in *Figure 13*. The calculated value of the geocentric velocity of this particle is $v_g = 16.8 \pm 0.3$ km/s. The Tisserand parameter with respect to Jupiter yields $T_J = 2.6$, which shows that this meteoroid followed a cometary orbit (JFC-type) before entering our atmosphere. In fact, according to the information found in the IAU meteor database, these results show that the fireball was a December ψ-Cassiopeiid (DPC#0446). This minor meteor shower, which is produced by meteoroids from

[31] https://youtu.be/PVyBB6-CTtg

Comet 3D/Biela, reaches its activity peak around December 4 (Jenniskens et al., 2016).

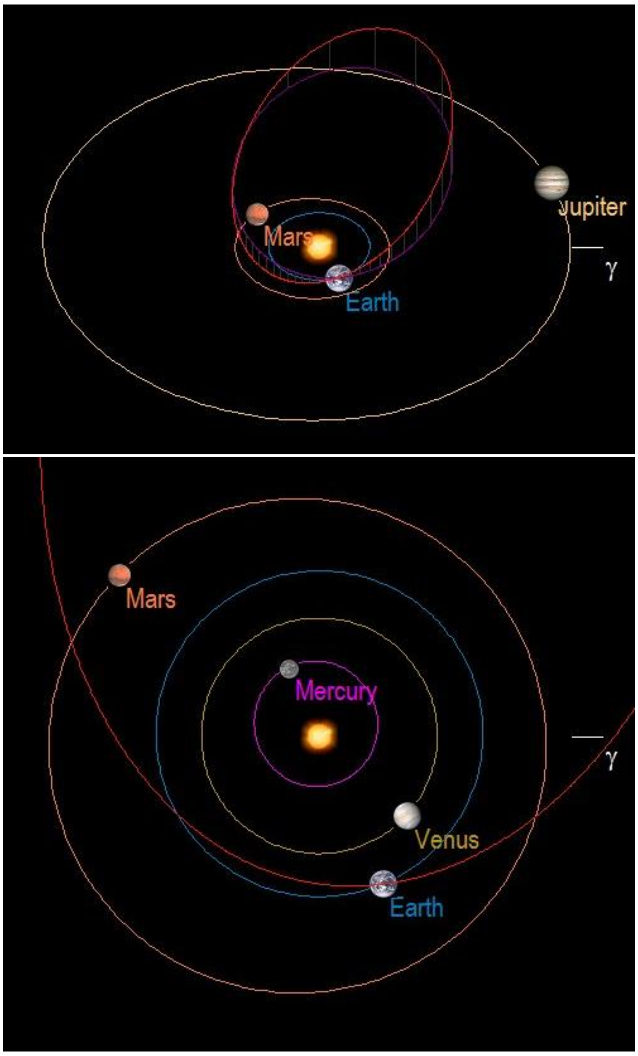

Figure 13 – Up: orbit (red line) of the parent meteoroid of the SWEMN20211128_223903 fireball, and its projection (violet line) on the ecliptic plane; Down: close-up view of the orbit.

9 The 2021 December 7 fireball

This bolide was recorded at $21^h31^m16.9 \pm 0.1^s$ UTC on 2021 December 7 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 –12 ± 1 (*Figure 14*). A video about this fireball was uploaded to YouTube[32]. The meteor was included in the SWEMN meteor database with the code SWEMN20211207_213116.

Atmospheric path, radiant and orbit

According to our calculations, the meteoroid entered the atmosphere with an initial velocity $v_\infty = 22.0 \pm 0.3$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 69.0°$, $\delta = +14.7°$. The event overflew the province of Granada. It began at an altitude $H_b = 105.2 \pm 0.5$ km, and ended at a height $H_e = 31.9 \pm 0.5$ km. This atmospheric trajectory and its projection on the ground are shown in *Figure 15*. At its initial stage the event was located almost over the town of Gor, and so we named the bolide after this location.

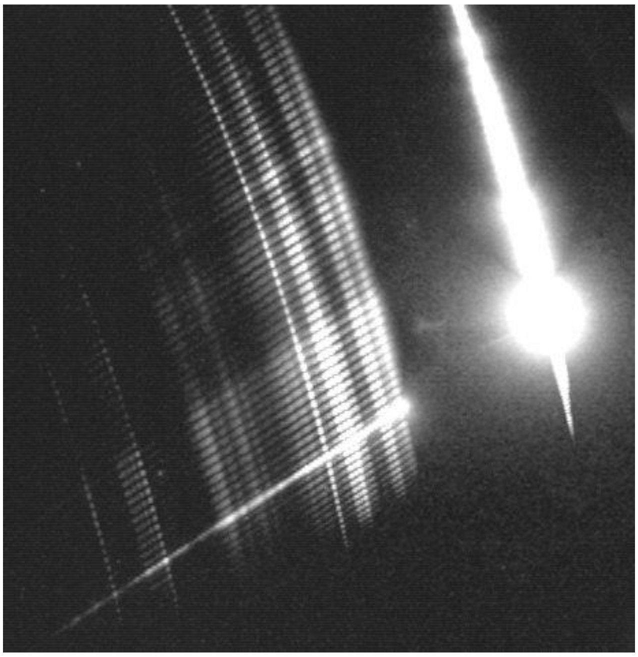

Figure 14 – Stacked image of the final stage of the SWEMN20211207_213116 "Gor" fireball as recorded from the Calar Alto Observatory. The image shows also the emission spectrum of the meteor.

Table 5 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20211207_213116 fireball.

a (AU)	2.24 ± 0.09	ω (°)	75.5 ± 0.3
e	0.69 ± 0.01	Ω (°)	75.67303 ± 10^{-5}
q (AU)	0.681 ± 0.003	i (°)	5.12 ± 0.05

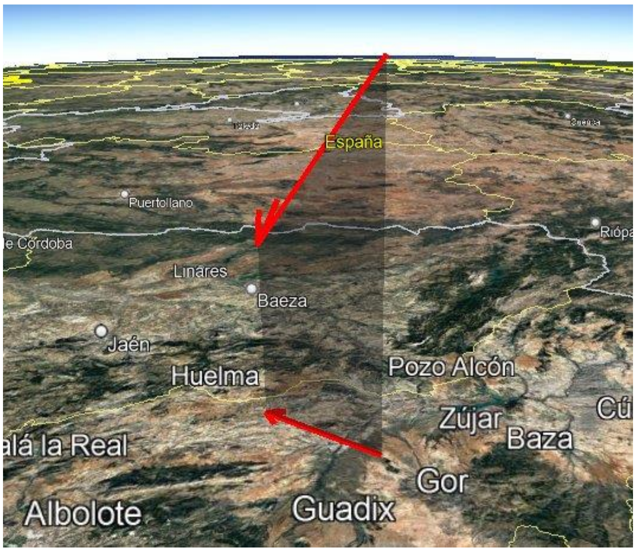

Figure 15 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20211207_213116 fireball.

Table 5 contains the orbital elements calculated for the parent meteoroid. This orbit is plotted in *Figure 16*. The calculated value of the geocentric velocity of this particle is $v_g = 18.7 \pm 0.3$ km/s. The Tisserand parameter with respect

[32] https://youtu.be/M2PE8AajxQM

to Jupiter yields $T_J = 3.2$, which shows that this meteoroid followed an asteroidal orbit before entering our atmosphere. Calculated radiant and orbital data do not match any of the meteoroid streams listed in the IAU meteor database. So, we classified this event as sporadic.

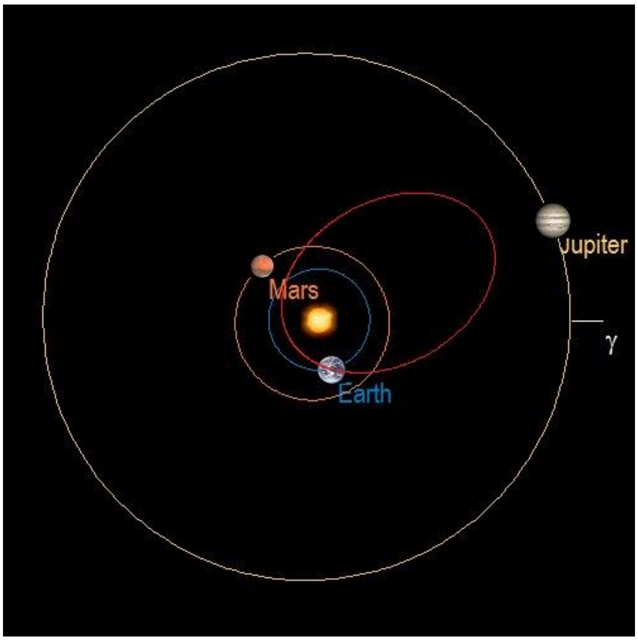

Figure 16 – Projection (red line) on the ecliptic of the orbit of the parent meteoroid of the SWEMN20211207_213116 fireball.

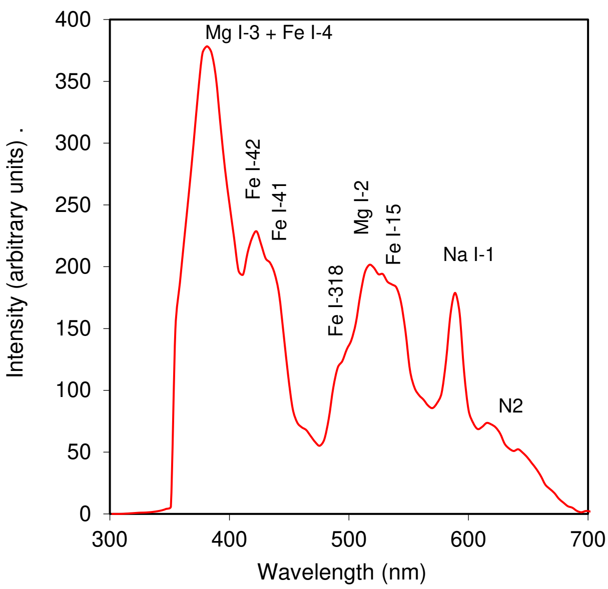

Figure 17 – Calibrated emission spectrum of the SWEMN20211207_213116 fireball.

Emission spectrum

One spectrograph located at Calar Alto recorded the emission spectrum of this event. The calibrated signal is shown in *Figure 17*, together with the most important emissions. The resolution of this spectrum is low, since there is a high degree of overlapping among the different multiplets. In spite of this, we have identified the emissions from Mg I-2, Fe I-15, Na I-2, Fe I-4, Mg I-3 and Fe I-318. Contributions from N2 bands are also present in the red region of the spectrum.

Figure 18 – Stacked image of the SWEMN20211214_001628 fireball as recorded from Calar Alto.

10 The 2021 December 14 fireball

This magnitude –12 ± 1 Geminid was recorded at $0^h16^m28.3 \pm 0.1^s$ UTC on 2021 December 14 from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, El Aljarafe, and Sierra Nevada (*Figure 18*). This is the brightest Geminid spotted from the Iberian Peninsula during the activity period of this shower in 2021. A video about this fireball was uploaded to YouTube [33]. The meteor was included in the SWEMN digital meteor database with the code SWEMN20211214_001628.

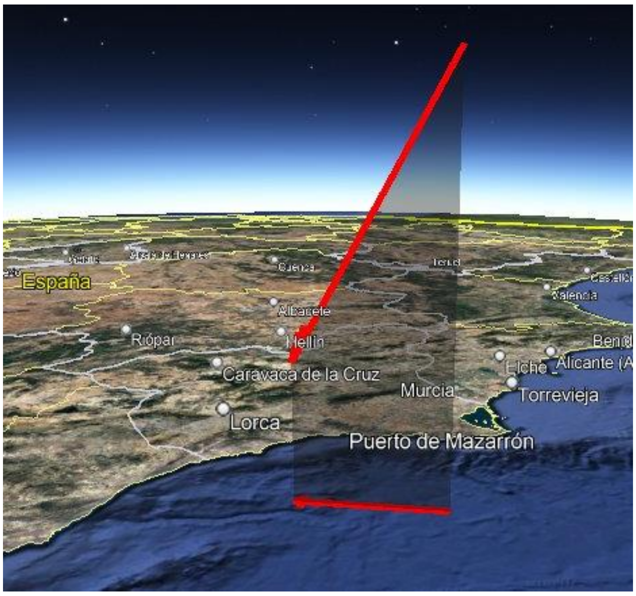

Figure 19 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20211214_001628 fireball.

[33] https://youtu.be/L_JjWkYCeJ8

Atmospheric path, radiant and orbit

According to our calculations, the meteoroid entered the atmosphere with an initial velocity $v_\infty = 36.4 \pm 0.3$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 118.9°$, $\delta = +30.5°$. The event overflew the Mediterranean Sea. It began at an altitude $H_b = 108.6 \pm 0.4$ km, and ended at a height $H_e = 35.6 \pm 0.4$ km over the sea. This atmospheric trajectory and its projection on the ground are shown in *Figure 19*.

Table 6 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20211214_001628 fireball.

a (AU)	1.10 ± 0.01	*ω* (°)	332.5 ± 0.1
e	0.910 ± 0.003	Ω (°)	261.92405 ± 10^{-5}
q (AU)	0.098 ± 0.003	*i* (°)	25.7 ± 0.5

Table 6 contains the orbital elements calculated for the parent meteoroid. This orbit is plotted in *Figure 20*. The calculated value of the geocentric velocity of this particle is $v_g = 34.4 \pm 0.3$ km/s. The Tisserand parameter with respect to Jupiter yields $T_J = 5.0$, which shows that this meteoroid followed an asteroidal orbit before entering our atmosphere. In fact, the information found in the IAU meteor database confirms that the meteoroid was associated with the Geminid stream (GEM#0004), whose parent body is Asteroid (3200) Phaethon.

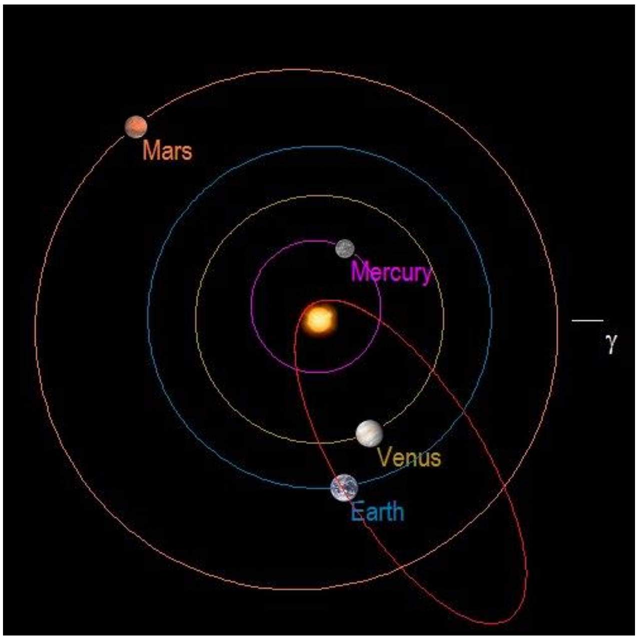

Figure 20 – Projection (red line) on the ecliptic of the orbit of the parent meteoroid of the SWEMN20211214_001628 fireball.

11 Conclusions

We have focused in this work on two new significant advances performed in the framework of the SWEMN network. One of them is related to the use of the SAMIA software and the AI in that program to automatically disseminate among the general public information about the most relevant fireballs recorded in the framework of the SMART project. Thus, by means of the information stored in the SWEMN digital database, SAMIA writes the texts necessary to disseminate this information on Twitter, Facebook, and YouTube. The software also can automatically write a press release to notify the media about these bolides.

The second advance discussed here has to do with the expansion of the SWEMN network during the last months. As a result of this, one new station named "El Aljarafe" entered operation near the city of Sevilla in October 2021. Besides, three additional video cameras were deployed between the last week of 2021 and the first week of 2022 at the meteor-observing station located at La Coruña (Galicia, NW of Spain). And currently, one new station is being setup at Mallorca to increase our coverage over the Mediterranean Sea, the south of France and the north of Africa.

We have also discussed the most remarkable fireballs recorded by our meteor-observing stations between September and December 2021. The peak absolute magnitude of these events ranged from –9 to –13.

The first of the bolides presented here was named "La Albuera". It was recorded on September 15, with a peak absolute magnitude of –12. This fireball, which was associated with the sporadic background, overflew the province of Badajoz and reached its final luminous stage with a non-zero terminal mass. The progenitor meteoroid followed an asteroidal orbit before entering our atmosphere. In the emission spectrum of this meteor we have identified the emissions from Fe I-4, Fe I-42, Fe I-41, Fe I-318, and Fe I-15, being the most prominent contributions those of the Mg I-2 triplet and the Fe I-15 multiplet. The emission from the Na I-1 is also remarkable, and the emission from Mg I-3 was also found.

The second fireball discussed in this work was the Madrigal de las Altas Torres event, which overflew the northwest of Spain on October 20 with a peak absolute magnitude of –9. Its progenitor meteoroid, which followed a long-period cometary orbit before entering the atmosphere, was associated with a poorly-known meteoroid stream: the κ-Aurigids (KAU#0537), whose proposed parent object is Comet C/1957U1(Latyshev-Wild-Burnham).

A deep-penetrating magnitude –13 Southern Taurid fireball was recorded on November 12. This event overflew the province of Salamanca, and reached a terminal height of about 25 km as a consequence of the high tensile strength of the meteoroid. Our calculations also reveal that the event exhibited a non-zero terminal mass (about 20 g) at the final stage of its luminous trajectory. An expedition was organized to the landing area of the surviving fragment(s), but unfortunately part of the area had just been plowed and the meteorite was not found.

Another bright fireball, with a peak absolute magnitude of –12, was recorded on November 28. The progenitor meteoroid was associated with Comet 3D/Biela. Thus, the event was a December ψ-Cassiopeiid (DPC#0446) that overflew the Atlantic Ocean around one week before the peak of this meteor shower.

The fireball named "Gor" was spotted on December 7. It was produced by a sporadic meteoroid following an asteroidal orbit. The bolide reached a peak absolute magnitude of –12 and overflew the province of Granada. The final height of this deep-penetrating event was of about 31 km. The emission spectrum of this meteor could be recorded. Despite its low resolution and high degree of line overlapping, we have identified in this signal the contributions from Mg I-2, Na I-1 and several neutral iron multiplets: Fe I-15, Fe I-4, Fe I-41, Fe I-42 and Fe I-318.

The last fireball we have included in this report is a magnitude –12 Geminid recorded by SWEMN stations on December 14. This bolide overflew the Mediterranean Sea and reached a final height of 35.3 km. This is the brightest Geminid observed from the Iberian Peninsula during the activity period of this shower in 2021.

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References

Borovička J. (1993). "A fireball spectrum analysis". *Astronomy & Astrophysics*, **279**, 627–645.

Ceplecha Z. (1987). "Geometric, dynamic, orbital and photometric data on meteoroids from photographic fireball networks". *Bull. Astron. Inst. Cz.*, **38**, 222–234.

Jenniskens P., Nénon Q., Albers J., Gural P. S., Haberman B., Holman D., Morales R., Grigsby B. J., Samuels D. and Johannink C. (2016). "The established meteor showers as observed by CAMS". *Icarus*, **266**, 331–354.

Madiedo J. M. (2014). "Robotic systems for the determination of the composition of solar system materials by means of fireball spectroscopy". *Earth, Planets & Space*, **66**, 70.

Madiedo J. M. (2015). "Spectroscopy of a κ-Cygnid fireball afterglow". *Planetary and Space Science*, **118**, 90–94.

Madiedo J. M., Ortiz J. L., Organero F., Ana-Hernández L., Fonseca F., Morales N. and Cabrera-Caño J. (2015a). "Analysis of Moon impact flashes detected during the 2012 and 2013 Perseids". *Astronomy & Astrophysics*, **577**, A118.

Madiedo J. M., Ortiz J. L., Morales N. and Cabrera-Caño J. (2015b). "MIDAS: Software for the detection and analysis of lunar impact flashes". *Planetary and Space Science*, **111**, 105–115.

Madiedo J. M., Espartero F., Castro-Tirado A. J., Pastor S., and De los Reyes J. A. (2016). "An Earth-grazing fireball from the Daytime ζ-Perseid shower observed over Spain on 2012 June 10". *Monthly Notices of the Royal Astronomical Society*, **460**, 917–922.

Madiedo J. M. (2017). "Automated systems for the analysis of meteor spectra: The SMART Project". *Planetary and Space Science*, **143**, 238–244.

Madiedo J. M., Ortiz J. L., Santos-Sanz P., Aceituno J. and de Guindos E. (2021). "The Southwestern Europe Meteor Network: recent advances and analysis of bright fireballs recorded along April 2021". *eMetN*, **6**, 397–406.

Ortiz J. L., Madiedo J. M., Morales N., Santos-Sanz P. and Aceituno F. J. (2015). "Lunar impact flashes from Geminids: analysis of luminous efficiencies and the flux of large meteoroids on Earth". *Monthly Notices of the Royal Astronomical Society*, **454**, 344–352.

Šegon D., Andreic Z., Gural P., Skokic I., Korlevic K., Vida D., Novoselnik F. and Gostinski D. (2014). "Results of CMN 2013 search for new showers across CMN and SonotaCo databases III". *WGN, Journal of the International Meteor Organization*, **42**, 227–233.

