Bright fireballs recorded along February 2021 in the framework of the Southwestern Europe Meteor Network

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This work focuses on the analysis of some of the brightest bolides recorded along February 2021 by the meteor-observing stations operating in the framework of the Southwestern Europe Meteor Network (SWEMN). Some of them were produced by meteoroids belonging to recently discovered and poorly-known streams. The absolute magnitude of these fireballs, which were observed over the Iberian Peninsula, ranged between –7 and –10. The emission spectra produced by some of these events are also presented and discussed.

1 Introduction

This work discusses a series of bright fireballs recorded over Spain by the Southwestern Europe Meteor Network (SWEMN) along February 2021. Weather conditions were not very favorable over most of the Iberian Peninsula during this period, mainly during the last two weeks of that month. This of course was a serious issue for SWEMN meteor stations, and these recorded less meteor events than average.

SWEMN was started by the Institute of Astrophysics of Andalusia (IAA-CSIC) with the aim to analyze the behavior and properties of meteoroids entering the Earth's atmosphere. For this purpose, SWEMN develops the Spectroscopy of Meteoroids by means of Robotic Technologies (SMART) survey. SMART, which started operation in 2006, is currently being carried out at 10 meteor-observing stations in Spain operated from IAA-CSIC (Madiedo, 2014; Madiedo, 2017). In 2021, four additional stations joined the project. These are operated from two universities in Spain: Public University of Navarra (UPNA) and Complutense University of Madrid (UCM).

SMART employs an array of automated cameras and spectrographs to determine the atmospheric trajectories of meteors and the orbit of their parent meteoroids, but also to analyze the composition of these particles from the emission spectrum produced by these meteors (see, e.g., Madiedo et al., 2013; Madiedo et al., 2014). It is worth mentioning that SMART works in close connection with the Moon Impacts Detection and Analysis System (MIDAS), which is a project conducted by the Institute of Astrophysics of Andalusia (Ortiz et al., 2015; Madiedo et al., 2018). The aim of the MIDAS survey is the identification and analysis of flashes generated when meteoroids hit the lunar ground, and the information provided by SMART allows to identify the most likely source of meteoroids impacting the Moon (Madiedo et al. 2015a,b; Madiedo et al. 2019).

Figure 1 – Stacked image of the SWEMN20210202_033000 "Albacete" fireball as recorded from La Sagra.

The bolides described here reached a peak absolute magnitude ranging from –7 to –10. All of them were simultaneously recorded from several SWEMN meteor-observing stations. In this way, their atmospheric path could be triangulated and the position of their radiant could be derived. We found that some of the bolides were associated with recently discovered and poorly-known meteoroid streams. The orbital elements of the meteoroids that gave rise to these meteor events were also calculated. In addition, we present the emission spectrum produced by some of these fireballs.

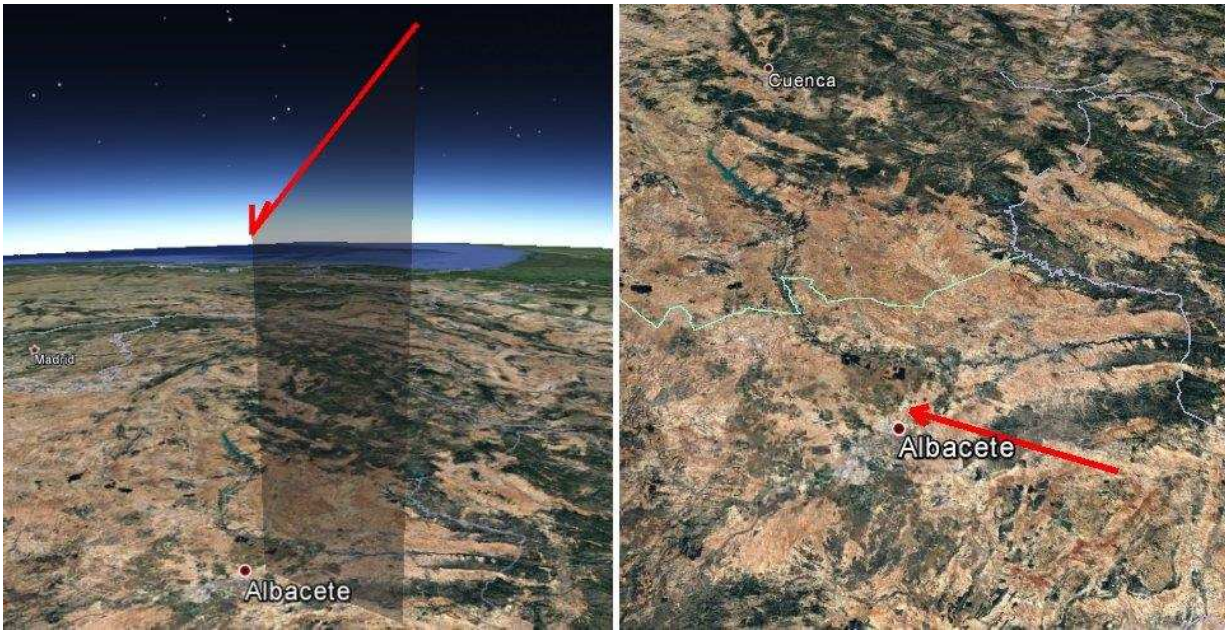

Figure 2 – Atmospheric path (left) and projection on the ground (right) of the trajectory of the SWEMN20210202_033000 "Albacete" fireball.

2 Instrumentation and methods

The bolides analyzed in this work were recorded by means of an array of black and white low-lux analog CCD video cameras manufactured by Watec Co. (models 902H and 902H2 Ultimate). To record meteor emission spectra, some of these devices are configured as spectrographs by attaching holographic 1000 lines/mm diffraction gratings to their objective lens. These Watec cameras have a resolution of 720 × 576 pixels, and their field of view ranges, approximately, from 62 × 50 degrees to 14 × 11 degrees in order to get a good accuracy in the calculation of meteor positions and velocities. 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 was given elsewhere (Madiedo, 2017).

At each meteor-observing station the cameras monitor the night sky and operate in a fully autonomous way. The atmospheric trajectory 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 to obtain the path of meteors in the atmosphere (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).

3 The 2021 February 2 bolide

On the night of 2021 February 2, at $3^h30^m00.0 \pm 0.1^s$ UTC, a fireball with a peak absolute magnitude of –7 ± 1 was recorded from the SWEMN meteor-observing stations located at the astronomical observatories of Calar Alto, La Sagra, La Hita, Sierra Nevada and Sevilla (*Figure 1*). This bolide was labeled in our meteor database with the code SWEMN20210202_033000.

Atmospheric path, radiant and orbit

The analysis of the atmospheric path of the bolide has been performed by taking into account the recordings from the different meteor-observing stations that observed the event. Our calculations reveal that it overflew the province of Albacete (*Figure 2*). The estimated pre-atmospheric velocity of the meteoroid is $v_\infty = 63.0 \pm 0.4$ km/s, with the apparent radiant located at the equatorial coordinates $\alpha = 226.2°$, $\delta = +14.4°$. The luminous event began at a height $H_b = 112.6 \pm 0.5$ km, and ended at an altitude $H_e = 75.9 \pm 0.5$ km. At its terminal point the bolide was almost over the vertical of the city of Albacete, and so it was named after this location. The atmospheric path of the fireball and its projection on the ground are shown in *Figure 2*.

Table 1 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210202_033000 "Albacete" fireball.

a (AU)	6.8 ± 1.6	ω (º)	185.9 ± 0.4
e	0.85 ± 0.03	Ω (º)	313.21583 ± 10^{-5}
q (AU)	0.9830 ± 0.0003	i (º)	119.8 ± 0.2

The calculated geocentric velocity of the meteoroid yields $v_g = 61.7 \pm 0.4$ km/s. The orbital parameters of the parent meteoroid before its encounter with our planet are listed in *Table 1*. This heliocentric orbit is shown in *Figure 3*. The value of the Tisserand parameter with respect to Jupiter (T_J = –0.1) reveals that the meteoroid followed a cometary orbit before entering the Earth's atmosphere. Radiant and orbital data reveal that said meteoroid belonged to the 12-Bootids stream (TBO#0607). This recently discovered and poorly known annual shower peaks around January 18 (Segon et al., 2014). The orbital elements listed in *Table 1* are in very good agreement with orbital parameters included in the IAU meteor database[2].

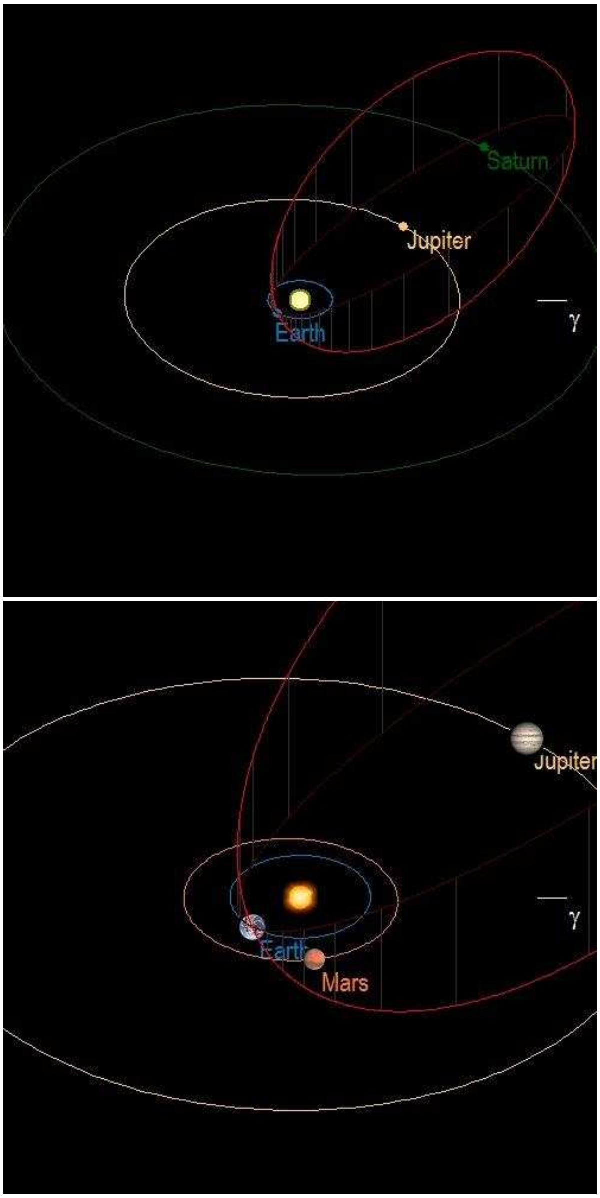

Figure 3 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210202_033000 fireball, and projection of this orbit (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

Emission spectrum

The emission spectrum of the fireball was recorded by one of our videospectrographs from Sierra Nevada. Meteor spectra with the resolution provided by our instruments typically allows to identify lines produced by Na, Mg, Ni, Fe, Ca and some metal oxides in the meteoroid, together with the contributions of atmospheric oxygen and nitrogen (see, for instance, Madiedo, 2014; Madiedo et al. 2021). Previous works performed from the Calar Alto Astronomical Observatory have shown that higher resolution spectra have proven to be useful to identify additional species, such as Ti, Cr, Zr, Pd and W (Passas et al., 2016).

As in previous works (Madiedo, 2015b), the spectrum was calibrated in wavelength and corrected by taking into account the spectral sensitivity of the device. The calibrated spectrum is shown in *Figure 4*, where the most significant lines have been highlighted. The majority of these contributions correspond to neutral iron (Fe I), which is typical in meteor spectra (Borovička, 1993; Madiedo, 2014). In this case, several multiplets of Fe I have been identified. The most important ones are Fe I-4 at 393.3 nm (which appears blended with the Mg I-3 line at 383.2 nm), Fe I-43 and Fe I-15. The most important contributions, however, correspond to the H and K lines of Ca II-1, which also appear blended in the signal. The emission lines of the Na I-1 doublet (588.9 nm) and the Mg I-2 triplet (516.7 nm) are also very significant. The contribution from Ca I-2 at 422.6 nm was also observed. Atmospheric N_2 bands were identified in the red region of the spectrum, together with the contribution from N I and the O I line at 777.1 nm. The analysis of the relative intensities of these lines will provide key information about the nature of the meteoroid.

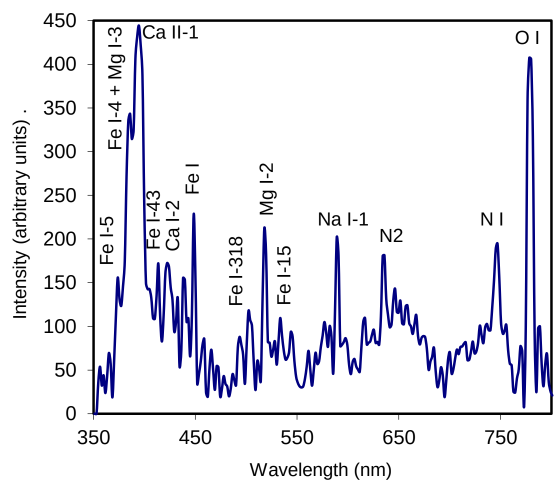

Figure 4 – Calibrated emission spectrum of the SWEMN20210202_033000 "Albacete" fireball.

4 The 2021 February 15 fireball

This event was detected by SWEMN systems on 2021 February 15 at $21^h38^m19.8 \pm 0.1^s$ UTC. Its peak absolute magnitude was –7 ± 1 (*Figure 5*). The bolide was recorded from the meteor-observing stations operating at La Sagra, Sierra Nevada, Calar Alto, El Arenosillo, and Sevilla. The fireball, which can be viewed on this YouTube video[3], was included in the SWEMN meteor database under the code SWEMN20210215_213819.

Atmospheric path, radiant and orbit

According to our calculations, this fireball overflew the provinces of Córdoba and Jaén, located in Andalusia (south of Spain). The meteoroid that gave rise to this luminous event entered the atmosphere with an initial velocity

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

[3] https://youtu.be/xWpdDZWss5o

v_∞ = 14.4 ± 0.3 km/s. The apparent radiant of the meteor was located at the equatorial coordinates α = 58.6º, δ = –17.3º. The bolide began at an altitude H_b = 92.1 ± 0.4 km over the south of the province of Córdoba. The terminal point of the fireball was reached at a height H_e = 64.0 ± 0.5 km over the province of Jaén, next to the vertical of Arjona. For this reason, we named this event after this town. The atmospheric trajectory of this slow bolide and its projection on the ground are shown in *Figure 6*.

Figure 5 – Stacked image of the SWEMN20210215_213819 "Arjona" fireball over one of the domes of the Sierra Nevada Astronomical Observatory.

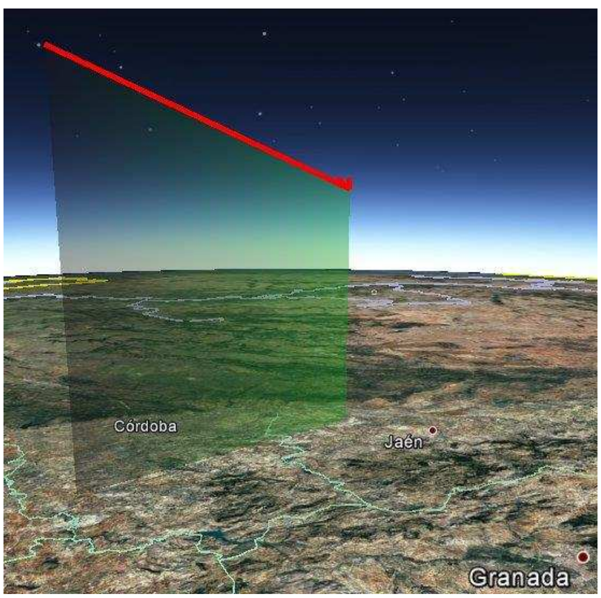

Figure 6 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210215_213819 "Arjona" fireball.

Once the atmospheric path was characterized, the orbital elements of the progenitor meteoroid were calculated. *Table 2* contains the orbital parameters obtained for this particle. This orbit is shown in *Figure 7*. The calculated geocentric velocity yields v_g = 9.6 ± 0.4 km/s. The value of the Tisserand parameter with respect to Jupiter (T_J = 3.5) shows that the meteoroid followed an asteroid-like orbit before its encounter with our planet. According to radiant and orbital data, this meteoroid belonged to the sporadic background.

Table 2 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210215_213819 "Arjona" fireball.

a (AU)	2.0 ± 0.1	ω (º)	343.5 ± 0.8
e	0.53 ± 0.03	Ω (º)	147.13489 ± 10^{-5}
q (AU)	0.9738 ± 0.0008	i (º)	10.5 ± 0.3

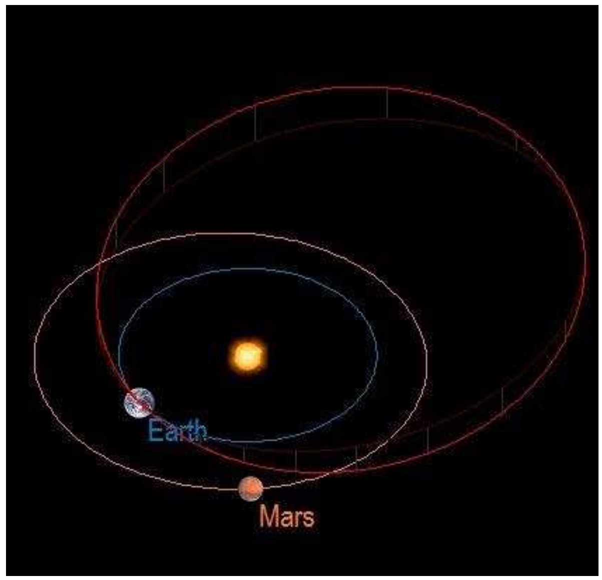

Figure 7 – Orbit (red line) of the parent meteoroid of the SWEMN20210215_213819 fireball, and its projection (dark red line) on the ecliptic plane.

5 The 2021 February 16 fireball

On the night of 2021 February 16, at $5^h00^m32.9 \pm 0.1^s$ UTC, a bolide with a peak absolute magnitude of –8 ± 1 was recorded by SWEMN systems operating from the astronomical observatories of La Hita, Sierra Nevada, El Arenosillo, Calar Alto, La Sagra, Sevilla and Madrid (*Figure 8*). A video showing this event was uploaded to YouTube[4]. After its appearance date and time, the fireball was included in our meteor database with the code SWEMN20210216_050033.

Atmospheric path, radiant and orbit

From the analysis of the recordings, we obtained that the event overflew the province of Badajoz (southwest of Spain). The pre-atmospheric velocity measured from the recordings was v_∞ = 61.8 ± 0.3 km/s. The bolide began at an altitude H_b = 117.7 ± 0.5 km over Badajoz and ended at a height H_e = 82.7 ± 0.5 km over the same province. We named this event "Villafranco del Guadiana", since the terminal point of its atmospheric path was located almost

[4] https://youtu.be/2cU4kn5tHBs

over the vertical of this town. The apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 196.9^{\circ}$, $\delta = -17.7^{\circ}$. The atmospheric trajectory of the fireball and its projection on the ground are shown in *Figure 9*.

Figure 8 – Stacked image of the SWEMN20210216_050032 "Villafranco del Guadiana" fireball as recorded from Sevilla.

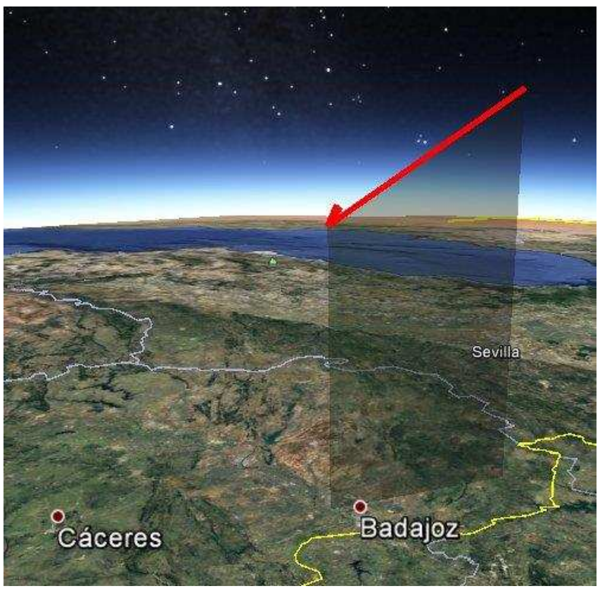

Figure 9 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210216_050032 fireball.

Table 3 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210216_050033 "Villafranco del Guadiana" fireball.

a (AU)	6.1 ± 0.9	ω (º)	118.9 ± 0.9
e	0.955 ± 0.005	Ω (º)	147.45544 ± 10^{-5}
q (AU)	0.271 ± 0.005	*i* (º)	148.7 ± 0.2

From the calculation of the orbital parameters of the progenitor meteoroid we derived the values listed in *Table 3*. The geocentric velocity yields $v_g = 60.9 \pm 0.3$ km/s. The orbit is shown in *Figure 10*. The calculated value of the Tisserand parameter with respect to Jupiter ($T_J = 0.3$) shows that this particle followed a cometary orbit before its encounter with our planet. Besides, radiant and orbital data reveal that the bolide was produced by a sporadic meteoroid.

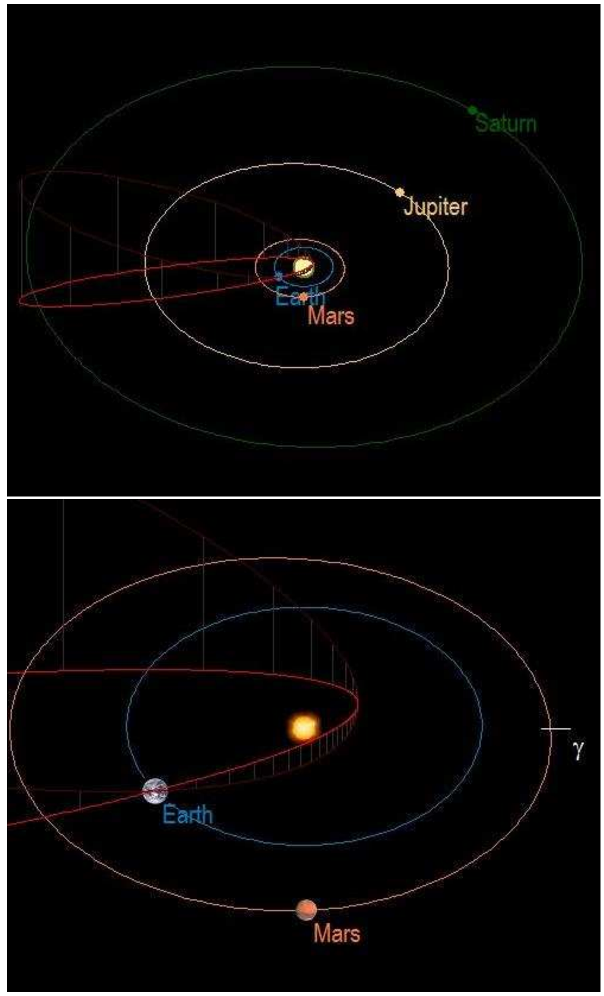

Figure 10 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210216_050032 fireball, and its projection (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

6 The 2021 February 17 fireball

This bolide was observed at $20^h35^m36.5 \pm 0.1^s$ UTC on 2021 February 17 (*Figure 11*). It exhibited several flares along its atmospheric trajectory as a consequence of the disruption of the progenitor meteoroid. The fireball reached a peak absolute magnitude of -10 ± 1. This event was spotted from the meteor-observing stations operating at the astronomical observatories of La Hita, La Sagra, Calar Alto, Sierra Nevada, El Arenosillo and Sevilla. It was recorded by our HD cameras. A video showing this fireball and its trajectory can be viewed on YouTube[5]. The bolide was included in our meteor database with the code SWEMN20210217_203536.

Atmospheric path, radiant and orbit

According to our calculation, the meteor was produced by a meteoroid that entered the atmosphere with an initial velocity $v_\infty = 27.6 \pm 0.3$ km/s. Its apparent radiant was located at the equatorial coordinates $\alpha = 146.8^{\circ}$, $\delta = +9.5^{\circ}$. This fireball also overflew the province of Badajoz, as the

[5] https://youtu.be/gvED_SpoX84

above-described event recorded the day before did. Thus, the bolide began at an altitude $H_b = 94.6 \pm 0.5$ km over Badajoz, and ended its luminous phase at a height $H_e = 43.9 \pm 0.4$ km over the same province. We named this fireball “Mérida”, since it overflew this city. *Figure 12* shows the atmospheric trajectory of this meteor and its projection on the ground.

Figure 11 – Stacked image of the SWEMN20210217_203536 “Mérida” fireball as recorded from Sevilla.

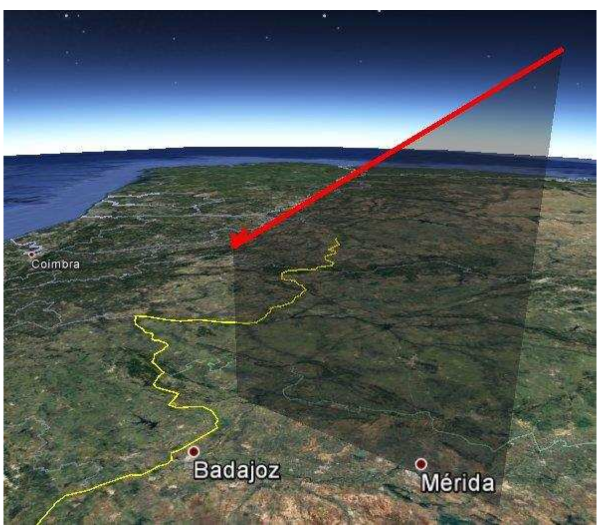

Figure 12 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210217_203536 “Mérida” fireball.

The results of the computation of the orbital elements of the meteoroid are listed in *Table 4*. The projection on the ecliptic plane of this orbit has been drawn in *Figure 13*. The geocentric velocity of the meteoroid yields $v_g = 25.1 \pm 0.3$ km/s. According to the data provided by the IAU meteor database, these results point to an association of this fireball with the February π-Leonids (FPL#0501), which peaks around February 6 (Rudawska and Jenniskens, 2014). The Tisserand parameter with respect to Jupiter, which yields $T_J = 2.19$, shows that the meteoroid followed a cometary orbit before its encounter with Earth, and suggests that this meteoroid stream is produced by a Jupiter family comet (JFC).

Table 4 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210217_203536 “Mérida” fireball.

a (AU)	4.0 ± 0.3	ω (°)	84.63 ± 0.08
e	0.85 ± 0.01	Ω (°)	149.09629 ± 10^{-5}
q (AU)	0.574 ± 0.002	i (°)	3.8 ± 0.1

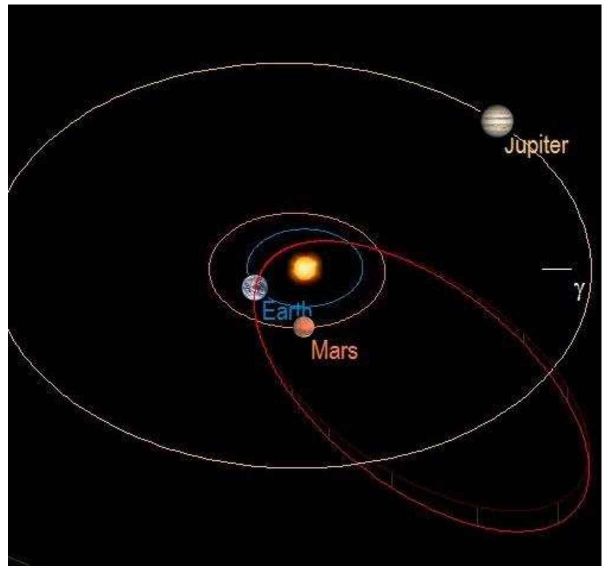

Figure 13 – Orbit (red line) of the parent meteoroid of the SWEMN20210217_203536 “Mérida” fireball, and its projection (dark red line) on the ecliptic plane.

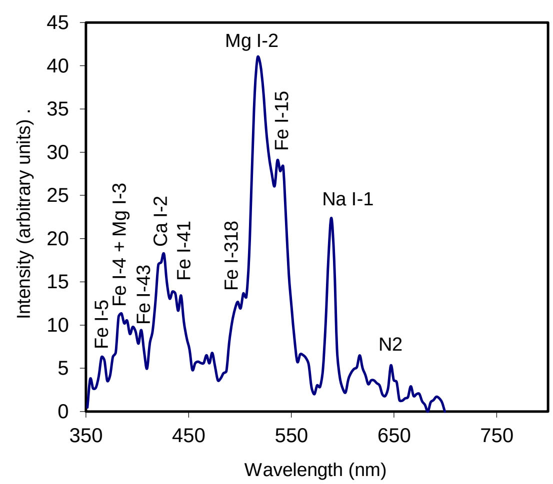

Figure 14 – Calibrated emission spectrum of the SWEMN20210217_203536 “Mérida” fireball.

Emission spectrum

The emission spectrum of the “Mérida” fireball was recorded from the meteor-observing station located at La Hita Astronomical Observatory. *Figure 14* shows this signal, which was corrected by taking into account the sensitivity of the spectrograph and calibrated in wavelength by means of the ChiMet software (Madiedo, 2015a). As can be noticed, the most relevant contributions correspond to the Na-I doublet (588.9 nm), the Mg I-2 triplet (516.7 nm), and the Fe I-15 emission. The contribution from Fe I-4 (393.3 nm) appears blended with the line produced by Mg

I-3 at 383.2 nm. Other neutral Fe multiplets have been identified, as for instance those of Fe I-5, Fe I-43, Fe I-41, and Fe I-318. The line of Ca I-2 at 422.6 nm was also found. Molecular bands produced by atmospheric N_2 are present in the red region of the spectrum.

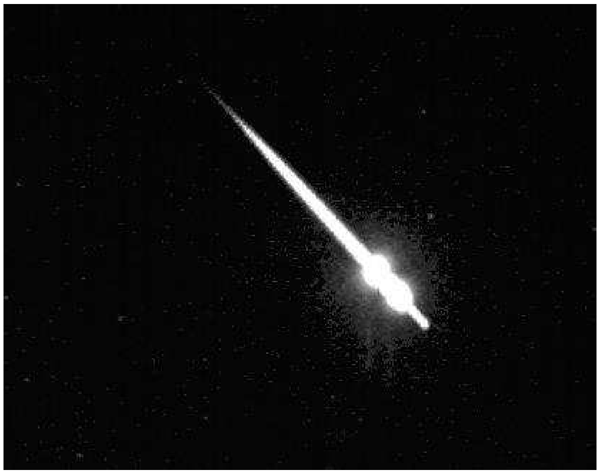

Figure 15 – Stacked image of the SWEMN20210218_043509 “Helechal” fireball as recorded from La Hita meteor station.

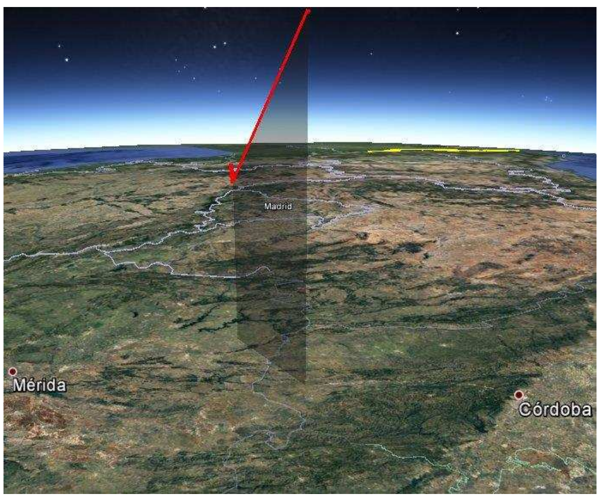

Figure 16 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210218_043509 fireball.

7 The 2021 February 18 fireball

This bolide reached a peak absolute magnitude of –9 ± 1, and was recorded at $4^h35^m09.4 \pm 0.1^s$ UTC on 2021 February 18. It experienced two bright flares, as can be seen in *Figure 15*. The event was spotted from the SWEMN meteor-observing stations deployed at La Hita, La Sagra, Calar Alto, Sevilla, Madrid, Sierra Nevada and El Arenosillo. A video showing this fireball was uploaded to YouTube[6]. The bolide was included in our meteor database with the code SWEMN20210218_043509.

Atmospheric path, radiant and orbit

The triangulation of the atmospheric trajectory of the meteor reveals that the meteoroid entered the atmosphere with an initial velocity v_∞ = 67.4 ± 0.5 km/s. The apparent radiant was located at the equatorial coordinates α = 223.1º, δ = +1.4º. The bolide began at an altitude H_b = 124.2 ± 0.5 km over the north of the province of Córdoba, and ended its luminous phase over the province of Badajoz, at a height H_e = 63.4 ± 0.5 km. The event exhibited its first major flare when it overflew Helechal, a village in the province of Badajoz. For this reason, we named the fireball after this location. *Figure 16* shows the atmospheric trajectory of the “Helechal” bolide and its projection on the ground.

Table 5 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210218_043509 “Helechal” fireball.

a (AU)	9.4 ± 4.0	*ω* (º)	244.5 ± 1.6
e	0.92 ± 0.03	Ω (º)	329.45156 ± 10^{-5}
q (AU)	0.717 ± 0.007	*i* (º)	147.1 ± 0.2

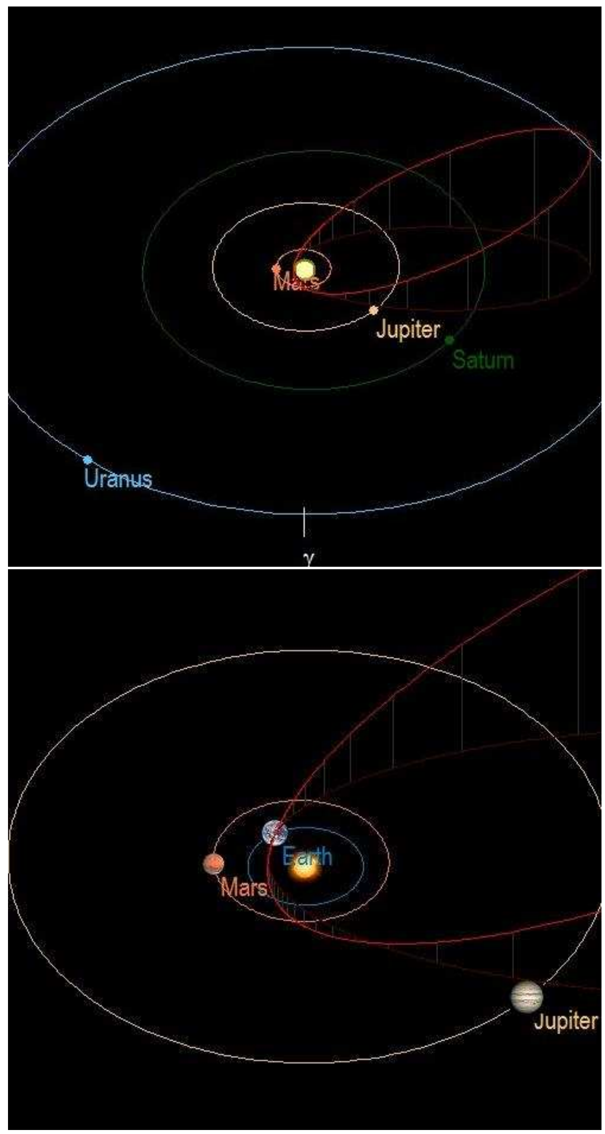

Figure 17 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210218_043509 fireball, and its projection (dark red line) on the ecliptic plane; Down: close-up view of the orbit.

The Amalthea software provided the values listed in *Table 5* for the orbital elements of the progenitor meteoroid. The

[6] https://youtu.be/91izm6gYv0g

projection on the ecliptic plane of this heliocentric orbit is shown in *Figure 17*. The calculated value of the geocentric velocity of this particle yields $v_g = 66.4 \pm 0.5$ km/s. According to the information found in the IAU meteor database, these results show that the meteoroid belonged to the February μ-Virginids (FMV#0516). This poorly-known meteoroid stream produces a display of meteors peaking around February 15 (Segon et al., 2013). The calculated value of the Tisserand parameter with respect to Jupiter (T_J = –0.3) shows that this meteoroid followed a cometary orbit before entering our atmosphere.

Emission spectrum

Four SWEMN spectrographs located at La Hita, La Sagra, and El Arenosillo recorded the emission spectrum of the "Helechal" bolide. The signal (*Figure 18*) was calibrated in wavelength and then corrected by taking into account the sensitivity of the recording device. As in previous cases, most features in the spectrum are associated with the emission of neutral iron. Thus, we have identified lines produced by Fe I-23, Fe I-5, Fe I-4, Fe I-318, Fe I-16 and Fe I-15. However, the most remarkable emission corresponds to the H and K lines of ionized calcium (Ca II-1 multiplet). Other relevant contributions are due to the Na-I doublet (588.9 nm), the Mg I-2 triplet (516.7 nm), Ca I-2 (422.6 nm), and Mg I-3 (383.2 nm). The latter is blended with the line produced by Fe I-4 at 393.3 nm. Molecular bands from atmospheric N_2 are also present in this case. A deeper analysis of this spectrum is currently in progress to derive information about the nature of the meteoroid.

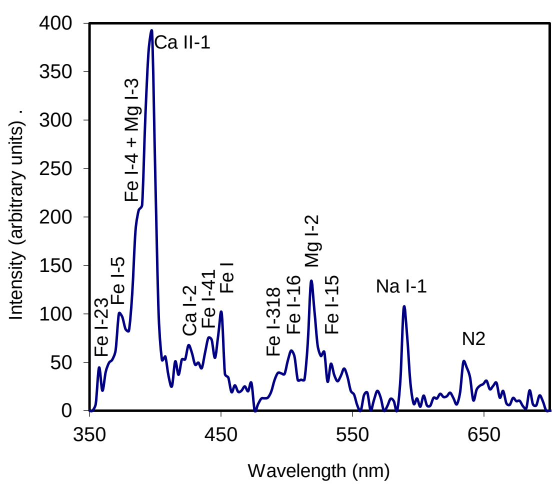

Figure 18 – Calibrated emission spectrum of the SWEMN20210218_043509 "Helechal" fireball.

8 Conclusion

We have presented here the five most relevant bolides recorded over Spain along February 2021 in the framework of the Southwestern Europe Meteor Network (SWEMN). The peak absolute magnitude of these fireballs ranged from –7 to –10. Our analysis has revealed that these events were produced by meteoroids belonging to the sporadic background, but also by members of recently-discovered meteoroid streams. So, our research has provided valuable information about the properties of poorly-known meteor showers.

The bolide recorded on February 2 (named "Albacete") was associated with the 12 Bootids (TBO#0607), a recently discovered meteoroid stream which peaks around January 18. It reached a peak absolute magnitude of –7. and the meteoroid followed a cometary orbit before hitting the Earth's atmosphere.

The bolide "Arjona", which was recorded on February 15, was produced by a sporadic meteoroid following an asteroidal orbit. This fireball overflew the provinces of Córdoba and Jaén, and reached a peak absolute magnitude of –7.

Another sporadic fireball (named "Villafranco del Guadiana") was spotted on February 16. In this case, the meteoroid followed a cometary orbit before entering the atmosphere. This event, which had a peak absolute magnitude of –8, overflew the province of Badajoz.

The mag. –10 "Merida" bolide, which also overflew the province of Badajoz, was recorded on February 17. It was associated with the February π-Leonids (FPL#0501), a poorly-known meteor shower which peaks around February 6. According to our results, the meteoroid followed a Jupiter family comet orbit before entering the atmosphere.

Finally, the mag. –9 "Helechal" fireball was found to be generated by a meteoroid belonging to the February μ-Virginid meteoroid stream. This bolide, which overflew the provinces of Córdoba and Badajoz, was recorded on February 18, three days after the peak of this meteor shower.

We have also recorded and presented the emission spectra obtained for the three shower bolides described in this work: "Albacete", "Mérida" and "Helechal". The main emission lines appearing in these spectra have been identified, and most of them were found to be produced by several neutral iron multiplets. The contributions from other chemical species contained in the progenitor meteoroids, such as those of Na I, Mg I, Ca I, and Ca II, were also identified. Atmospheric contributions were present in these signals too. Further analysis of these spectra is being performed to derive chemical information about the the 12-Bootids, the February π-Leonids, and the February μ-Virginids. This will allow us to improve our knowledge about these recently-discovered and poorly-known meteoroid streams.

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