Fireballs recorded between May and July 2021 by the Southwestern Europe Meteor Network

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This work focuses on the analysis of the most remarkable bolides recorded over the Iberian Peninsula and neighboring areas in the framework of the Southwestern Europe Meteor Network (SWEMN) and the SMART project. These events were spotted from May to July 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. For this purpose, we monitor the interaction of meteoroids with both the Earth and the Moon. 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). With the recent deployment of a new SWEMN meteor-observing station at the facilities of La Casa de las Ciencias de La Coruña (Galicia, Spain), this Institution has started to collaborate with this research network in June 2021.

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). SMART was started as a professional project in 2006. But since some amateur astronomers expressed their interest in establishing some kind of collaboration with us, we decided in 2021 to convert SMART into a Pro-Am project.

Besides, from IAA-CSIC we conduct 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,2015b; Madiedo et al., 2019b).

This work presents the most remarkable fireball events recorded along May, June, and July 2021 by our systems.

2 Instrumentation and methods

The bolides analyzed in this work 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).

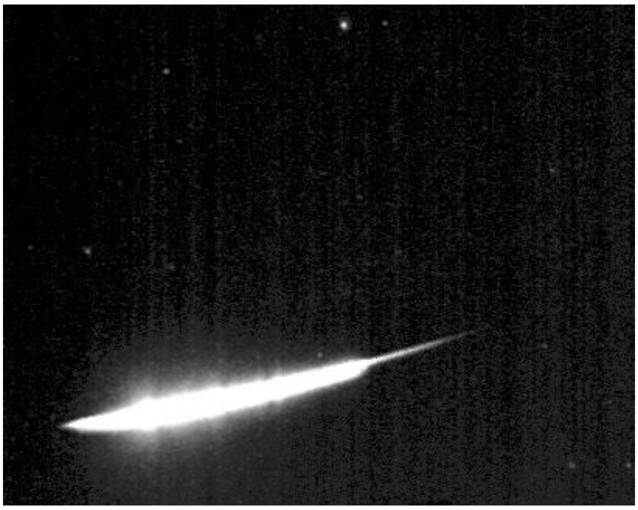

Figure 1 – Stacked image of the SWEMN20210516_223207 “Benicasim” fireball as recorded from the SWEMN meteor-observing station at La Hita Astronomical Observatory.

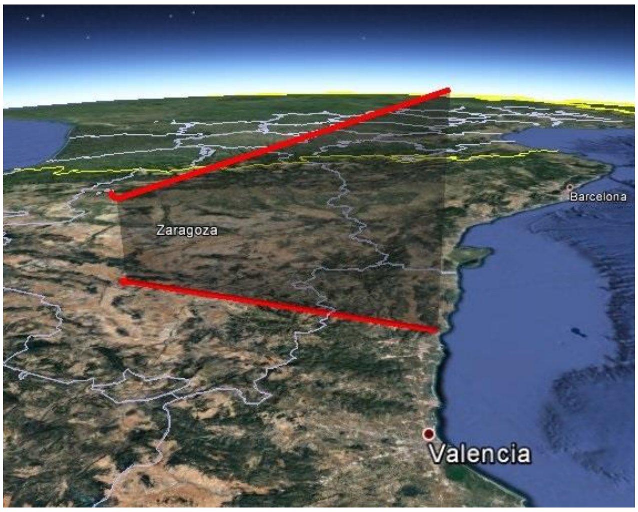

Figure 2 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210516_223207fireball.

3 The 2021 May 16 bolide

At $22^h32^m07.2 \pm 0.1^s$ UTC on May 16, we recorded a bolide from the SWEMN stations operating at La Hita, La Sagra, and Calar Alto. The event had a peak absolute magnitude of –9 ± 1 (*Figure 1*). This fireball was included in our new digital meteor database (Madiedo et al., 2021) with the code SWEMN20210516_223207.

Table 1 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210516_223207 fireball.

a (AU)	2.29 ± 0.14	*ω* (º)	317.1 ± 0.7
e	0.926 ± 0.005	Ω (º)	55.96078 ± 10^{-5}
q (AU)	0.168 ± 0.004	*i* (º)	8.5 ± 0.2

Atmospheric trajectory, radiant and orbit

The analysis of the recordings revealed that this bolide overflew the provinces of Castellón (region of Valencia) and Teruel (region of Aragón). We obtained a pre-atmospheric velocity for the progenitor meteoroid of $v_\infty = 37.7 \pm 0.4$ km/s, with the apparent radiant at the equatorial coordinates $\alpha = 256.1°$, $\delta = -17.21°$. The meteor began at a height $H_b = 94.4 \pm 0.5$ km, and ended at an altitude $H_e = 38.9 \pm 0.5$ km. The zenith angle of this trajectory was of about 69º. Since the initial point of the bolide’s path was almost over the vertical of the town of Benicasim (Castellón), we named the fireball after this location. The atmospheric path of the meteor and its projection on the ground are shown in *Figure 2*.

The calculated geocentric velocity of the progenitor meteoroid yields $v_g = 35.8 \pm 0.4$ km/s. The orbital parameters of this particle before its encounter with our planet are shown in *Table 1*, and this orbit is drawn in *Figure 3*. The information found in the IAU meteor database[6] shows that the fireball belonged to the phi Ophiuchids (USG#0809). This poorly-known meteoroid stream produces every year a display of meteors peaking around May 11. NEO 2015 DU180, a potentially hazardous asteroid (PHA), has been proposed as its parent body (Amaral et al., 2020). However, according to the calculated value of the Tisserand parameter with respect to Jupiter ($T_J = 2.7$), the meteoroid followed a Jupiter Family Comet orbit before impacting the Earth’s atmosphere.

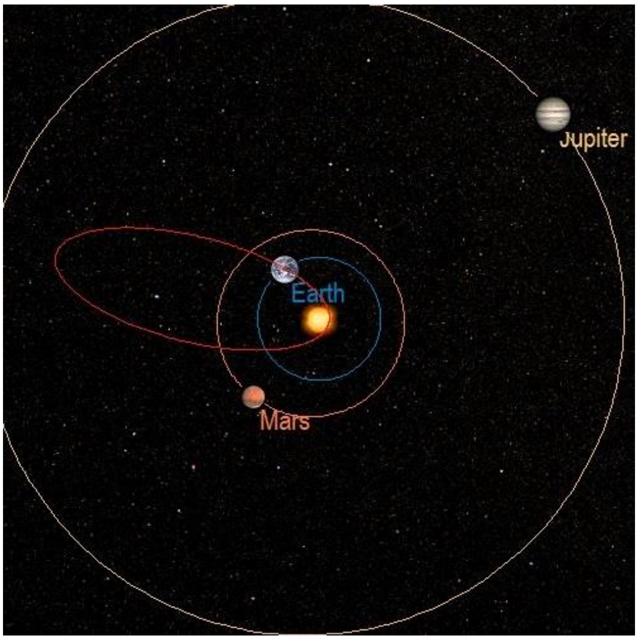

Figure 3 – Projection (dark red line) on the ecliptic plane of the orbit of the parent meteoroid of the SWEMN20210516 “Benicasim” fireball.

Emission spectrum

The emission spectrum of the SWEMN20210516_223207 fireball was recorded by our spectrographs from the astronomical observatories of Calar Alto and La Hita. 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, 2015b; Passas et al., 2016). The calibrated spectrum is shown in *Figure 4*, where the most remarkable contributions have been highlighted. The majority of these correspond to neutral iron, as usual in

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

meteor spectra (Borovička, 1993; Madiedo, 2014). Thus, we have identified the emissions from Fe I-4, Fe I-41, Fe I-318, Fe I-15, and Fe I-686. The most important emissions are those of Fe I-4, Ca I-2, and the Mg I-2 triplet (516.7 nm). The Na I-11 doublet is also remarkable, and the contribution from atmospheric N2 is present in the red part of the spectrum.

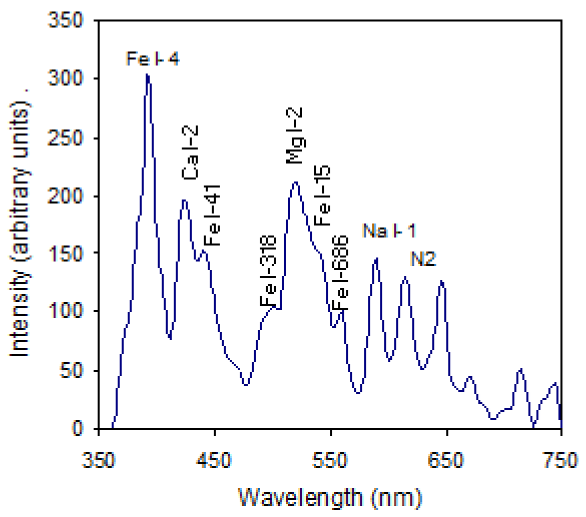

Figure 4 – Calibrated emission spectrum of the SWEMN20210516_223207 "Benicasim" fireball.

4 The 2021 June 12 fireball

This fireball reached a peak absolute magnitude of –8 ± 1. It was recorded on 2021 June 12 at $22^h05^m48.3 \pm 0.1^s$ UTC from the SWEMN meteor-observing stations operating at La Sagra, La Hita, Madrid, Sevilla, Sierra Nevada and Calar Alto. A video showing the event can be viewed on YouTube[7]. The bolide was included in our database under the code SWEMN20210612_220548.

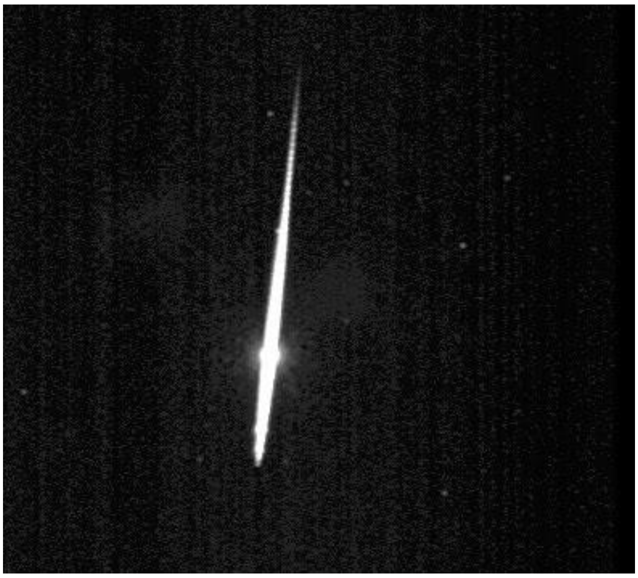

Figure 5 – Stacked image of the SWEMN20210612_220548 "Siruela" fireball as recorded from the SWEMN meteor-observing station located at La Hita Observatory.

Atmospheric path, radiant and orbit

The analysis of the trajectory reveals that this fireball overflew the northeast of the province of Badajoz (region of Extremadura). The meteoroid hit the atmosphere with an initial velocity $v_\infty = 19.2 \pm 0.3$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 236.39°$, $\delta = +52.72°$. The calculated atmospheric path and its projection on the ground are shown in *Figure 6*. The bolide began at an altitude $H_b = 89.7 \pm 0.5$ km, near from the vertical of the town of Siruela (province of Badajoz). For this reason, we named the event in our database after this location. The terminal point of its luminous path was reached at a height $H_e = 40.8 \pm 0.5$ km over the northeast of the same province. This atmospheric trajectory had a zenith angle of around 15º.

Figure 6 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210612_220548 fireball.

Table 2 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210612_220548 fireball.

a (AU)	2.59 ± 0.14	ω (º)	189.36 ± 0.03
e	0.61 ± 0.02	Ω (º)	81.84937 ± 10^{-5}
q (AU)	1.0104 ± 0.0001	i (º)	22.9 ± 0.4

From the calculation of the orbital elements of the meteoroid we obtained the results are listed in *Table 2*. The corresponding orbit is drawn in *Figure 7*. The value derived for the geocentric velocity is $v_g = 15.6 \pm 0.3$ 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 are consistent with a fireball belonging to the τ-Herculids (TAH#0061). This meteor shower is associated with Comet 73P/Schwassmann-Wachmann 3 and peaks around June 2.

[7] https://youtu.be/3l8gk3S8jbs

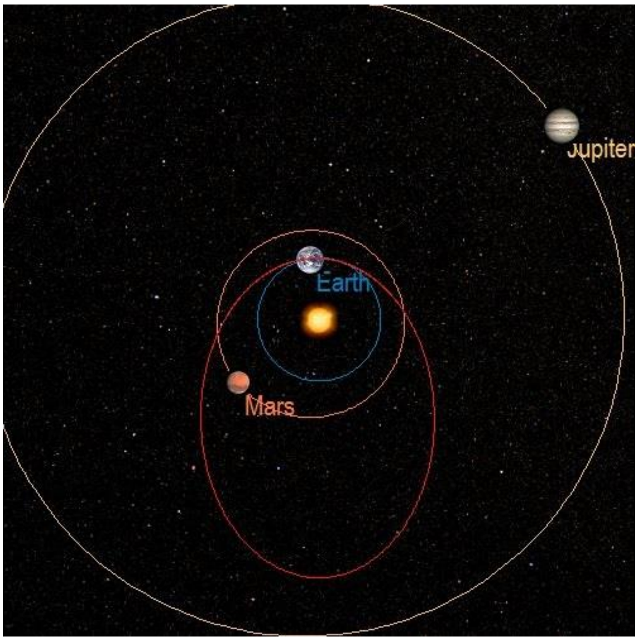

Figure 7 – Projection on the ecliptic plane (red line) of the orbit of the parent meteoroid of the SWEMN20210612_220548 fireball.

5 The 2021 June 14 fireball

This bolide was observed on 2021 June 14, at $21^h33^m14.0 \pm 0.1^s$ UTC. It was recorded from the SWEMN meteor-observing stations located at El Arenosillo, La Hita, La Sagra, Calar Alto, Sevilla, and Sierra Nevada. It reached a peak absolute magnitude of –9 ± 1 (*Figure 8*). A video about this fireball was uploaded to YouTube[8]. The meteor was included under the code SWEMN20210614_213314 in the SWEMN meteor database.

Atmospheric path, radiant and orbit

According to our analysis, the pre-atmospheric velocity of the meteoroid yields $v_\infty = 14.4 \pm 0.2$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 197.0°$, $\delta = -28.28°$. The event overflew the provinces of Málaga and Sevilla (Andalusia). It began at an altitude $H_b = 83.4 \pm 0.5$ km over the southwest of the province of Málaga, and ended at a height $H_e = 38.4 \pm 0.5$ km over the east of the province of Sevilla. At this final stage the event was located almost over the vertical of the town of Casariche, and so we named the bolide after this location. This atmospheric trajectory of the event and its projection on the ground are shown in *Figure 9*.

Table 3 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210614_213314 fireball.

a (AU)	2.18 ± 0.11	*ω* (°)	15.7 ± 0.1
e	0.54 ± 0.02	Ω (°)	263.76246 ± 10^{-5}
q (AU)	1.0023 ± 0.0006	*i* (°)	9.06 ± 0.07

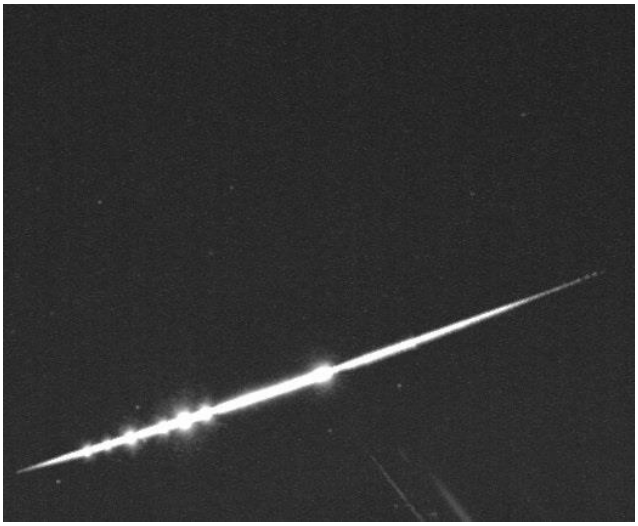

Figure 8 – Stacked image of the SWEMN20210614_213314 "Casariche" fireball as recorded from the SWEMN meteor-observing station located at El Arenosillo Observatory.

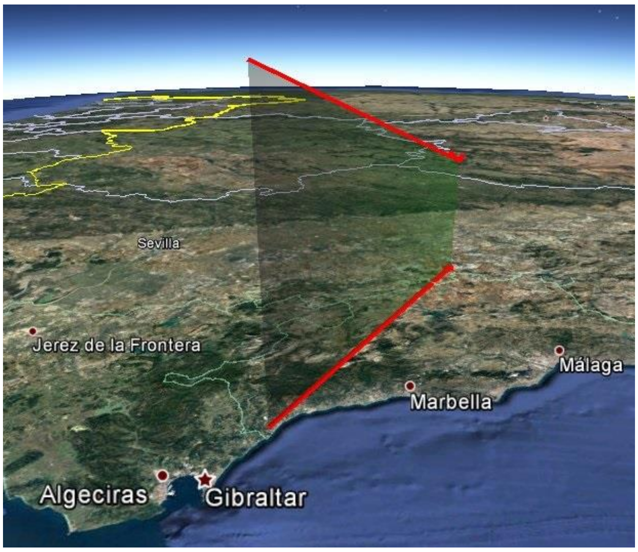

Figure 9 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210614_213314 fireball.

The orbital elements calculated for the parent meteoroid are listed in *Table 3*. This orbit is drawn in *Figure 10*. The value calculated for the geocentric velocity of this particle yields $v_g = 9.5 \pm 0.3$ km/s. The Tisserand parameter with respect to Jupiter yields $T_J = 3.4$, which suggests that this meteoroid followed an asteroidal orbit before entering the atmosphere. According to the information contained in the IAU meteor database, these results show that the fireball was associated with the Corvids (COR#0063). This meteor shower peaks around June 26, and the potentially hazardous asteroid 2004 HW has been suggested as parent body (Jenniskens et al., 2016).

[8] https://youtu.be/ASnLydyCVHI

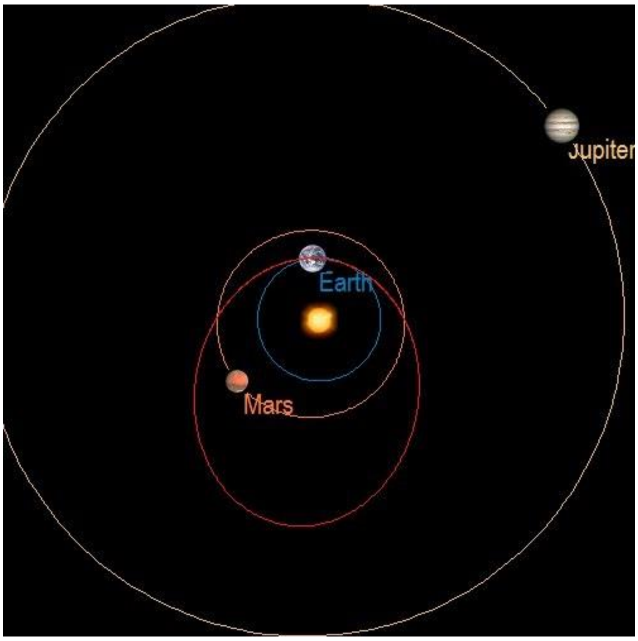

Figure 10 – Projection on the ecliptic plane (red line) of the orbit of the parent meteoroid of the SWEMN20210614_213314 fireball.

Figure 11 – Stacked image of the SWEMN20210723_220040 “Ibros” fireball as recorded from Calar Alto.

6 Fireball on 2021 July 23

This bright bolide was observed by a wide number of casual eyewitnesses along Spain at $22^h00^m40.8 \pm 0.1^s$ UTC on 2021 July 23. Some of these reported this event by means of our online fireball report form. The fireball was also recorded from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, El Arenosillo, Madrid, and Sierra Nevada. It reached a peak absolute magnitude of –11 ± 1 (*Figure 11*), and a video about this fireball was uploaded to YouTube[9]. The meteor was included in the SWEMN meteor database with the code SWEMN20210723_220040.

Atmospheric path, radiant and orbit

The analysis of the images recorded by our meteor cameras revealed that the bolide overflew the provinces of Ciudad Real (region of Castilla-La Mancha) and Jaén (Andalusia). The meteoroid entered the atmosphere with an initial velocity $v_\infty = 23.4 \pm 0.4$ km/s, and the apparent radiant of the fireball was located at the equatorial coordinates $\alpha = 274.9°$, $\delta = +34.0°$. Its atmospheric trajectory and the corresponding projection on the ground are shown in *Figure 12*. The event began at an altitude $H_b = 85.2 \pm 0.5$ km over the south of Ciudad Real, and ended at a height $H_e = 35.1 \pm 0.5$ km over Jaén. We named this bolide “Ibros”, since at this final stage it was located almost over the vertical of this town in the province of Jaén.

Table 4 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210723_220040 fireball.

a (AU)	1.95 ± 0.08	ω (°)	152.9 ± 0.5
e	0.50 ± 0.02	Ω (°)	120.96300 ± 10^{-5}
q (AU)	0.9788 ± 0.0005	i (°)	34.1 ± 0.5

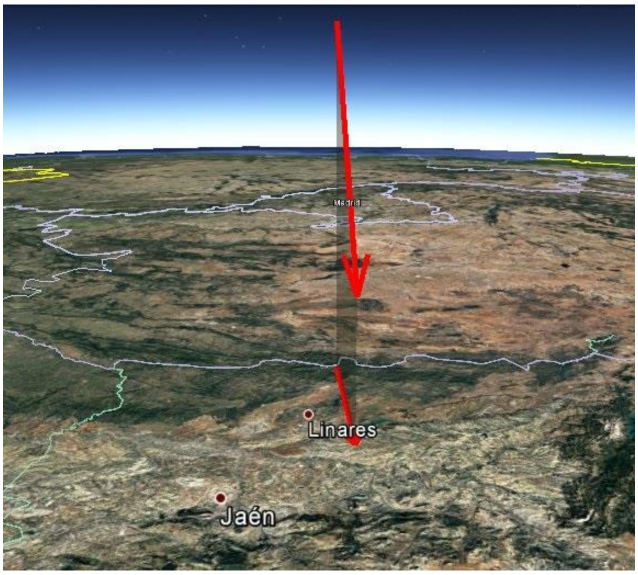

Figure 12 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210723_220040 fireball.

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 meteoroid yields $v_g = 20.7 \pm 0.4$ km/s. The Tisserand parameter with respect to Jupiter yields $T_J = 3.5$, which shows that this particle followed an asteroidal orbit before entering our atmosphere. The orbital and radiant data obtained from our analysis do not match any of the meteor showers listed in the IAU meteor database. So, this fireball was associated with the sporadic background.

[9] https://youtu.be/5FmxYSaDkZk

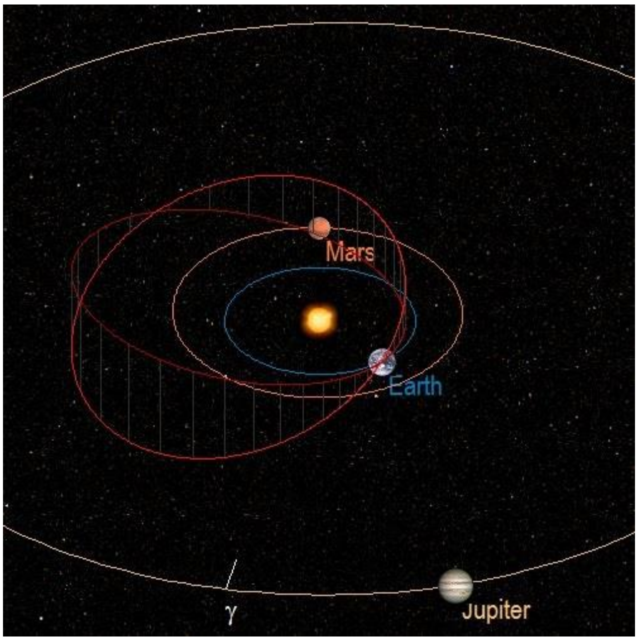

Figure 13 – Orbit (light red line) of the parent meteoroid of the SWEMN20210723_220040 fireball, and its projection (dark red line) on the ecliptic plane.

Figure 14 – Stacked image of the SWEMN20210731_211843 "Cebolla" fireball as recorded from La Hita Astronomical Observatory.

7 Fireball on 2021 July 31

On 2021 July 31, a wide number of casual eyewitnesses observed a very bright fireball crossing the night sky over Spain at $21^h18^m43.0 \pm 0.1^s$ UTC. The event was also recorded from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, Madrid, and Sierra Nevada. It reached a peak absolute magnitude of –9±1 (*Figure 14*). A video about this fireball was uploaded to YouTube[10]. The meteor was included in the SWEMN meteor database with the code SWEMN20210731_211843.

Atmospheric path, radiant and orbit

The meteoroid that gave rise to this bolide hit the atmosphere at $v_\infty = 59.1 \pm 0.5$ km/s. The apparent radiant of the resulting meteor was located at the equatorial coordinates $\alpha = 33.7°$, $\delta = +55.8°$. The event overflew the provinces of Segovia, Madrid and Toledo. It began at an altitude $H_b = 138.9 \pm 0.5$ km over the northeast of Segovia, crossed the west of Madrid, and ended at a height $H_e = 81.1 \pm 0.5$ km over the west of Toledo. This atmospheric trajectory and its projection on the ground are shown in *Figure 15*. At its ending point the event was located over the town of Cebolla, and so we named the meteor after this location.

Table 5 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210731_211843 fireball.

a (AU)	8.7 ± 3.1	ω (°)	146.1 ± 0.8
e	0.89 ± 0.03	Ω (°)	128.58516 ± 10^{-5}
q (AU)	0.933 ± 0.002	i (°)	111.3 ± 0.3

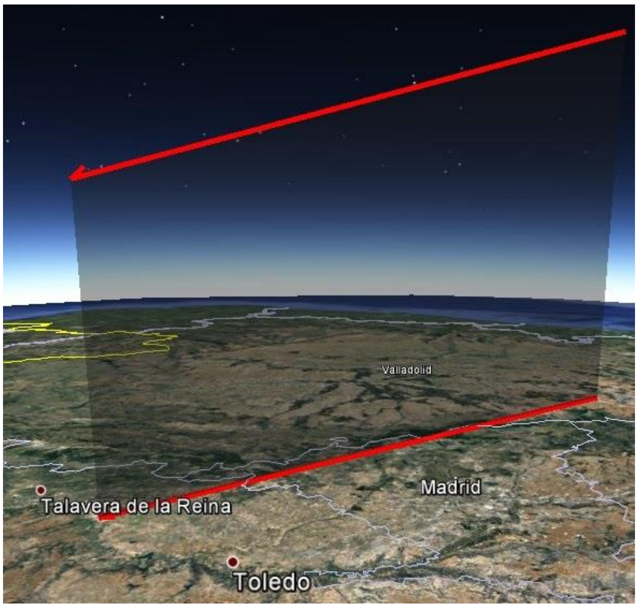

Figure 15 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210731_211843 fireball.

From this information we have calculated the orbital elements of the progenitor meteoroid. These are listed in *Table 5*, and the orbit is plotted in *Figure 16*. The calculated value of the geocentric velocity of this particle is $v_g = 57.8 \pm 0.5$ km/s, and the Tisserand parameter with respect to Jupiter yields $T_J = 0.1$. The value of this parameter suggests that this meteoroid followed a cometary orbit before entering our atmosphere. These results indicate that the fireball was a bright Perseid (IAU code PER#0007) that occurred about two weeks before the peak of this meteor shower.

Emission spectrum

The emission spectrum of this bright Perseid was recorded by the SWEMN spectrographs located at La Hita Observatory. The calibrated signal is shown in *Figure 17* shows the calibrated signal, together with the most important emissions. As can be noticed, the most important

[10] https://youtu.be/sjomWIRhdB0

contributions are those from Fe I-4 and the H and L lines of ionized calcium (Ca II-1). Additional contributions from neutral iron have been also found, and the most significant ones are those from Fe I-23, Fe I-43, Fe I-42, Fe I-41, Fe I-318, and Fe I-15. The lines produced by Mg I-2 and Na I-1 are also present. The emission from atmospheric N2 bands in the red region of the spectrum are also noticeable.

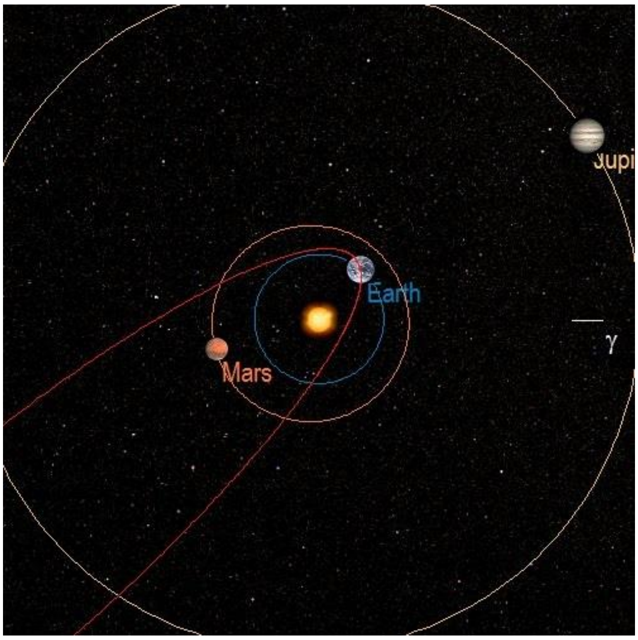

Figure 16 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20210731_211843 fireball.

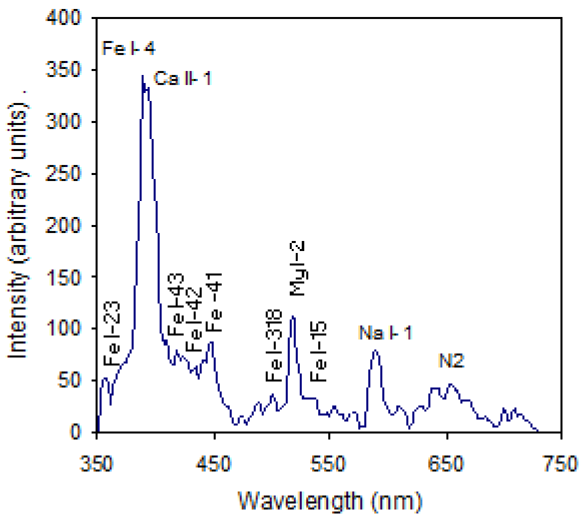

Figure 17 – Calibrated emission spectrum of the SWEMN20210731_211843 fireball.

8 Conclusion

In this work we have presented the most relevant bolides recorded in the framework of the SWEMN meteor network from May to July 2021. Their peak absolute magnitude ranged from –8 to –11.

The first event analyzed here was the magnitude –9 "Benicasim" bolide. This was recorded on 2021 May 16 and overflew the provinces of Castellón and Teruel. It was associated with the phi-Ophiucids, a minor meteor shower that has been associated with a PHA (2015 DU180). The value obtained for the Tisserand parameter with respect to Jupiter, however, suggests that the progenitor meteoroid followed a JFC orbit instead of an asteroidal orbit. The spectrum of this bolide is dominated by the contributions from Fe I-4, Ca I-2, and Mg I-2. It also contains the contribution from the Na I-1 doublet and several neutral iron multiplets.

A mag. –8 τ-Herculid bolide was recorded on June 12. It overflew the province of Badajoz. We named this event "Siruela". Two nights later, on June 14, the magnitude –9 Corvid fireball named "Casariche" overflew the provinces of Málaga and Sevilla. Our results are consistent with an asteroidal origin of the Corvid stream, which has been associated with the potentially hazardous asteroid 2004 HW.

The sporadic fireball "Ibros" reached a peak absolute magnitude of –11. This is the brightest event presented in this work, and a wide number of eyewitnesses observed it from all over the Iberian Peninsula. It overflew the provinces of Ciudad Real and Jaén (south of Spain) on 2021 July 23. Our results suggest an asteroidal origin of the progenitor meteoroid, which would belong to the sporadic background.

The last bright meteor included in this report is the Perseid named "Cebolla", which ended over this town in the west of the province of Toledo after crossing the provinces of Segovia and Madrid. Its peak luminosity was equivalent to a stellar magnitude of –9. It was spotted on 2021 July 31, and a wide number of casual eyewitnesses could observe it. We have also presented the emission spectrum of this bolide. The most remarkable contributions in this spectrum are those produced by Fe I-4 and Ca II-1 (H and L lines of single-ionized calcium). The contributions from several neutral iron multiplets are also present, together with those of Mg I-2 and Na I-1.

Acknowledgment

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