Remarkable bolides recorded along August 2021 in the framework of the Southwestern Europe Meteor Network

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The most remarkable fireballs observed along August 2021 in the framework of the Southwestern Europe Meteor Network (SWEMN) and the SMART project are presented in this work. These fireballs overflew the Iberian Peninsula and neighboring areas, and reached an absolute peak luminosity ranging between mag. –8 and –12. The emission spectra of some of these bright meteors are also discussed.

1 Introduction

The Southwestern Europe Meteor Network (SWEMN) is a research network coordinated in Spain by the Institute of Astrophysics of Andalusia (IAA-CSIC) with the aim to analyze the Earth's meteoric environment. Currently the 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). We also have support from the National Institute of Aerospace Technology (INTA), and receive input from amateur astronomers who collaborate with this meteor network.

The Spectroscopy of Meteoroids by means of Robotic Technologies (SMART) is being developed in the framework of the SWEMN network to identify and analyze meteors in the Earth's atmosphere. This systematic survey began in 2006 (Madiedo, 2014; Madiedo, 2017). To obtain a much more complete insight into the properties of the Earth-Moon meteoric environment, SMART works in close connection with another project conducted by the Institute of Astrophysics of Andalusia: The Moon Impacts Detection and Analysis System (MIDAS) (Ortiz et al., 2015; Madiedo et al., 2018). Thus, SMART employs our atmosphere as a detector to identify meteors generated by meteoroids crossing the Earth's orbit. At the same time, MIDAS considers the Moon as a laboratory that provides information about meteoroids hitting the lunar ground (Madiedo et al., 2019a). Previous works showed that there exists a strong synergy between both systems (Madiedo et al. 2015a,b; Madiedo et al. 2019b).

We present in this work an analysis of the most remarkable bolides recorded during August 2021 over Spain and neighboring areas by the Southwestern Europe Meteor Network. Their peak absolute magnitude ranges from –8 to –12 Their atmospheric path was triangulated and the orbit of the progenitor meteoroid was also obtained. We discuss also the emission spectrum recorded for some of these meteors.

2 Instrumentation and methods

The meteors described here 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, 2015).

Figure 1 – Stacked image of the SWEMN20210803_195954 "Valdepeñas" fireball as recorded from the SWEMN meteor-observing station deployed at the Calar Alto Observatory.

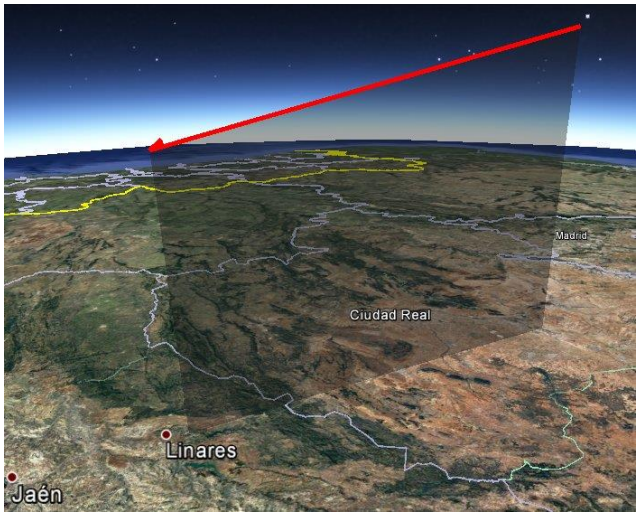

Figure 2 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210803_195954 "Valdepeñas" fireball.

3 The 2021 August 3 bolide

This fireball was a Perseid observed about 10 days before the activity peak of this meteor shower. The event was spotted at $19^h59^m54.3 \pm 0.1^s$ UTC on August 3 (*Figure 1*). It had a peak absolute magnitude of -8 ± 1, and was recorded by the cameras deployed at Calar Alto, La Sagra, La Hita, Sevilla, and El Arenosillo. We labeled it in the SWEMN meteor database with the code SWEMN20210803_195954.

Atmospheric trajectory, radiant and orbit

The atmospheric path of the bolide and its projection on the ground are shown in *Figure 2*. From the calculation of this trajectory, we obtained that it overflew the provinces of Ciudad Real (region of Castilla-La Mancha) and Jaén (Andalusia). The observed pre-atmospheric velocity of the meteoroid is $v_\infty = 59.4 \pm 0.3$ km/s, with the apparent radiant located at the equatorial coordinates $\alpha = 36.0^o$, $\delta = +58.3^o$. The meteor began at a height $H_b = 105.5 \pm 0.5$ km, and ended at an altitude $H_e = 78.4 \pm 0.5$ km. It overflew the town of Valdepeñas in the province of Ciudad Real, and so we named the bolide after this location.

Table 1 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210803_195954 "Valdepeñas" fireball.

a (AU)	62 ± 98	ω (º)	149.3 ± 0.4
e	0.98 ± 0.02	Ω (º)	131.40337 ± 10^{-5}
q (AU)	0.944 ± 0.001	i (º)	109.4 ± 0.1

The geocentric velocity of the progenitor meteoroid yields $v_g = 58.2 \pm 0.3$ km/s, and its orbital parameters are listed in *Table 1*. This heliocentric orbit is drawn in *Figure 3*. Radiant and orbital data indicate a clear association with the Perseid meteoroid stream according to the information included in the IAU meteor database[17].

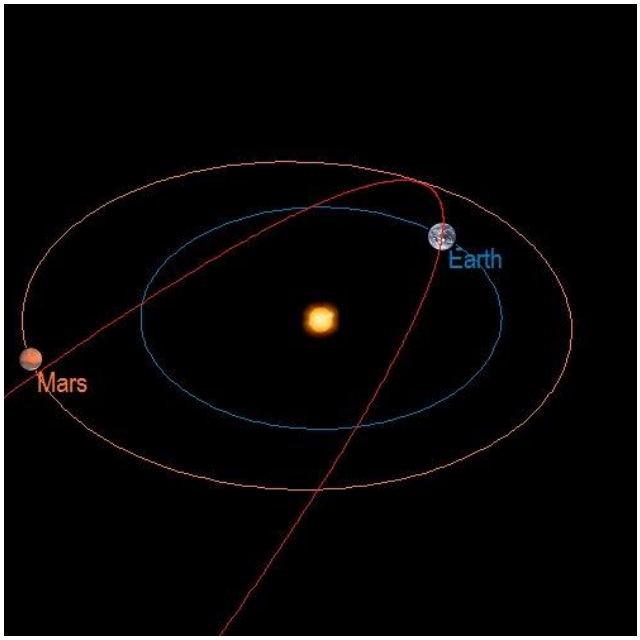

Figure 3 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20210803_195954 fireball.

4 The 2021 August 5 fireball

This stunning bolide was recorded by our cameras on 2021 August 5 at $0^h22^m10.6 \pm 0.1^s$ UTC. It reached a peak absolute magnitude of -12 ± 1 as a consequence of a flare that occurred at the end of its atmospheric path (*Figure 5*). It was spotted from the SWEMN meteor-observing stations operating at La Sagra, Sierra Nevada, Calar Alto, La Hita, El Arenosillo, and Sevilla. The fireball, which can be viewed on this YouTube video[18], was included in the

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

[18] https://youtu.be/AcqysKKjn04

SWEMN meteor database under the code SWEMN20210805_002210.

Atmospheric path, radiant and orbit

The analysis of the images revealed that the fireball began over the Mediterranean Sea, next to the coast of the province of Almería (Andalusia). The parent meteoroid of this bolide entered the atmosphere with an initial velocity $v_\infty = 24.3 \pm 0.3$ km/s. The apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 311.9^o$, $\delta = -5.1^o$. The bolide began at an altitude $H_b = 104.4 \pm 0.5$ km over the sea, over the vertical of a point located at about 5 km of the coast of Spain. It moved northwest and overflew Almería, reaching its terminal point at a height $H_e = 73.1 \pm 0.5$ km over the north of this province. This trajectory and its projection on the ground are shown in *Figure 6*. We named this event "Villaricos", since the fireball overflew an area next to the vertical of this town.

Figure 5 – Stacked image of the SWEMN20210805_002210 "Villaricos" fireball as recorded from the Calar Alto Astronomical Observatory.

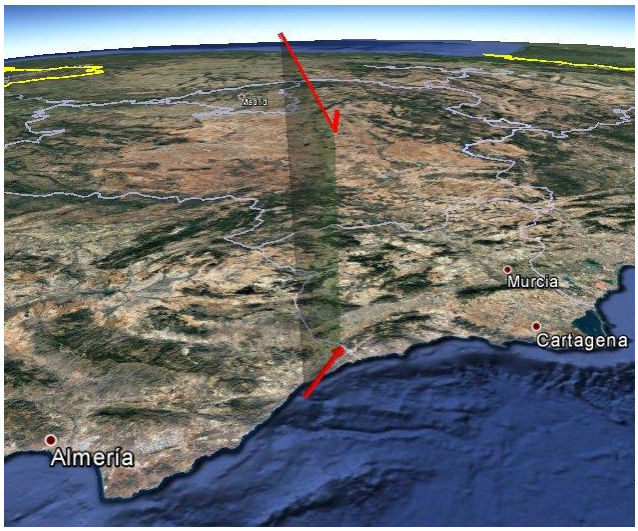

Figure 6 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210805_002210 "Villaricos" fireball.

The calculated orbit of the parent meteoroid is drawn in *Figure 7*, and the value of the corresponding orbital elements are included in *Table 2*. The geocentric velocity of the particle yields $v_g = 21.6 \pm 0.3$ km/s. Besides, the value of the Tisserand parameter with respect to Jupiter ($T_J = 2.9$) shows that this meteoroid followed a cometary orbit (JFC type). According to radiant and orbital information listed in the IAU Meteor Data Center, this particle belonged to the α-Capricornid stream (CAP#0001), whose parent body is Comet 169P/NEAT and produces an annual display of meteors with a peak activity around August 1 (Jenniskens et al., 2016).

Table 2 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210805_002210 "Villaricos" fireball.

a (AU)	2.48 ± 0.10	ω (º)	265.51 ± 0.03
e	0.75 ± 0.01	Ω (º)	132.51817 ± 10^{-5}
q (AU)	0.612 ± 0.003	i (º)	7.2 ± 0.1

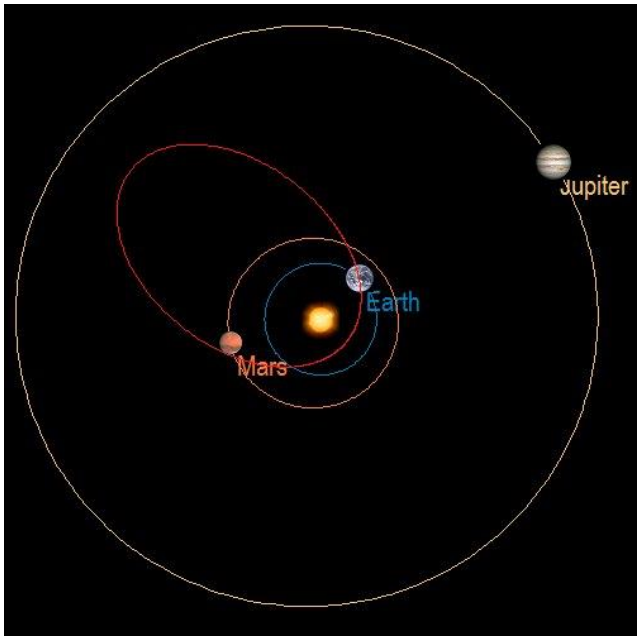

Figure 7 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20210805_002210 fireball.

5 The 2021 August 10 fireball

A fireball with a peak luminosity equivalent to an absolute magnitude of -8 ± 1 was recorded by our systems on August 10, at $0^h55^m23.4 \pm 0.1^s$ UTC from the meteor-observing stations located at La Hita, Sierra Nevada, Calar Alto, La Sagra, and Sevilla (*Figure 8*). A video showing images of this event and information about its trajectory was uploaded to YouTube[19]. This bright meteor was included in the SWEMN digital database with the code SWEMN20210810_005523.

Atmospheric path, radiant and orbit

Our analysis shows that the event overflew the provinces of Ciudad Real and Albacete (region of Castilla-La Mancha). The pre-atmospheric velocity observed in this case was $v_\infty = 13.5 \pm 0.3$ km/s. The bolide began at an altitude $H_b = 79.2 \pm 0.5$ km over the southeast of the province of Ciudad Real and ended at a height $H_e = 45.6 \pm 0.5$ km over the west of the province of Albacete. We named this meteor "Viveros", since at this final stage the bolide was located

[19] https://youtu.be/OO8kGKtIhGA

almost over the vertical of this town. The apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 269.1^{o}$, $\delta = +1.4^{o}$. Its atmospheric trajectory and the corresponding projection on the ground are shown in *Figure 9*.

Figure 8 – Stacked image of the SWEMN20210810_005523 "Viveros" fireball as recorded from the Calar Alto Observatory.

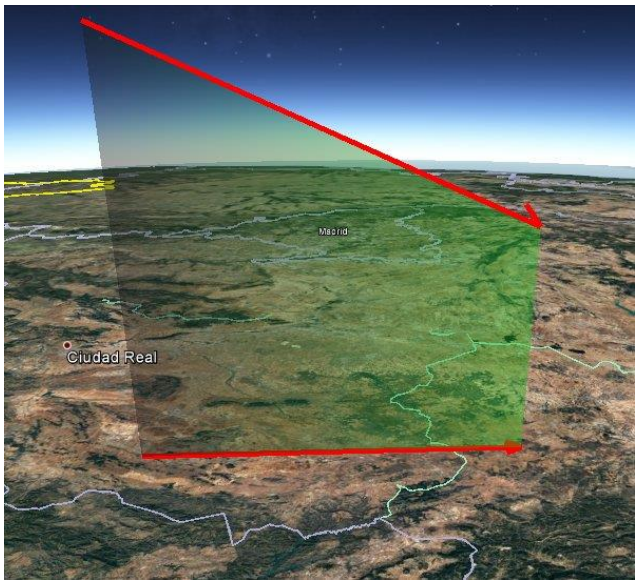

Figure 9 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210810_005523 fireball.

Table 3 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210810_005523 "Viveros" fireball.

a (AU)	2.3 ± 0.1	ω (º)	195.9 ± 0.6
e	0.56 ± 0.03	Ω (º)	137.30106 ± 10-5
q (AU)	0.999 ± 0.001	i (º)	2.3 ± 0.4

The heliocentric orbit of the progenitor meteoroid is shown in *Figure 10*, and the calculated orbital parameters are listed in *Table 3*. The geocentric velocity obtained for this particle is $v_g = 8.2 \pm 0.5$ km/s. According to these results we concluded that this meteoroid followed an asteroidal orbit before its encounter with our planet, since the Tisserand parameter with respect to Jupiter yields $T_J = 3.3$. In addition, since we found no match in the IAU meteor database, we associated this particle with the sporadic background.

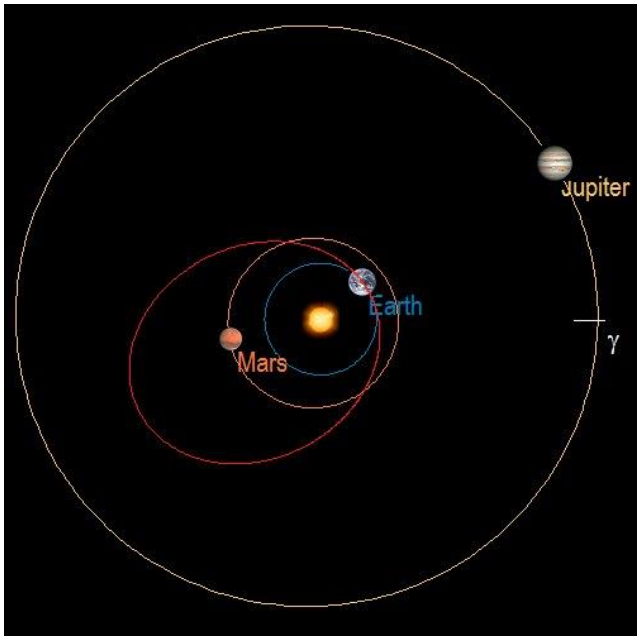

Figure 10 – Projection on the ecliptic plane of the orbit (red line) of the parent meteoroid of the SWEMN20210810_005523 fireball.

6 The 2021 August 12 fireball

A very bright Perseid bolide was recorded by the SWEMN network on the 12th of this month, at $21^{h}58^{m}32.1 \pm 0.1^{s}$ UTC. Besides, the fireball was observed by a wide number of eyewitnesses. Thus, many of them were observing the Perseids that night. The bolide reached a peak absolute magnitude of –12 ± 1 and, as can be seen in *Figure 11*, it exhibited several flares along its atmospheric trajectory as a consequence of the disruption of the meteoroid. The event was spotted from the meteor-observing stations operated by the SWEMN network at the astronomical observatories of La Hita, La Sagra, Sierra Nevada, Calar Alto, and El Arenosillo. It was included in our meteor database with the code SWEMN20210812_215832.

Atmospheric path, radiant and orbit

In this case the meteoroid hit the atmosphere with an initial velocity $v_\infty = 60.0 \pm 0.5$ km/s, and the apparent radiant was located at the equatorial coordinates $\alpha = 47.6^{o}$, $\delta = +59.2^{o}$. It overflew three provinces in central Spain: Segovia, Avila and Toledo. Thus, the bolide began at an altitude $H_b = 129.4 \pm 0.5$ km over the north of the province of Segovia. From that position it moved southwest and overflew the eastern part of the province of Avila and next the northwest of the province of Toledo. Finally, the fireball ended at a height $H_e = 75.1 \pm 0.5$ km over a point located near from the vertical of the town of Navamorcuende. We named the event after this location in the province of Toledo. *Figure 12* shows the atmospheric trajectory of this meteor and its projection on the ground.

In *Table 4* we have included the orbital elements of the meteoroid, and the heliocentric orbit is drawn in *Figure 13*.

The geocentric velocity of the particle yields v_g = 58.8 ± 0.5 km/s. As in the case of the bolide recorded by our meteor network on August 3 and discussed above, the information provided by the IAU meteor database implies that that this fireball was a Perseid. It was, besides, the brightest Perseid observed over the Iberian Peninsula during the activity period of this meteor shower in 2021.

Table 4 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210812_215832 "Navamorcuende" fireball.

a (AU)	25 ± 27	ω (º)	150.1 ± 0.7
e	0.96 ± 0.02	Ω (º)	140.41044 ± 10^{-5}
q (AU)	0.947 ± 0.001	*i* (º)	111.6 ± 0.3

Figure 11 – Stacked image of the SWEMN20210812_215832 "Navamorcuende" fireball as recorded from La Hita Observatory.

Figure 12 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210812_215832 fireball.

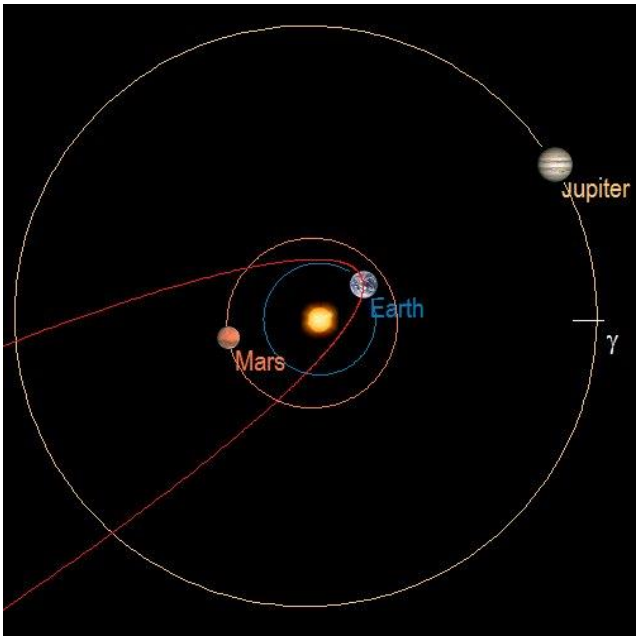

Figure 13 – Projection on the ecliptic plane of the orbit (red line) of the progenitor meteoroid of the SWEMN20210812_215832 fireball.

Emission spectrum

The emission spectrum of the fireball was obtained by our spectrographs located at La Hita. Calar Alto, and La Sagra meteor-observing stations. *Figure 14* shows the calibrated signal and the most important emissions in this spectrum. As usual in meteor spectra (Borovička, 1993), most lines correspond to neutral Fe emissions. Thus, we have identified the contributions from Fe I-5, Fe I-43, Fe I-41, Fe I-318 and Fe I-15. The most remarkable lines are those of Fe I-4 and Ca II-1, which appear blended, and the line of O I at 778 nm. The emissions from multiplets Ca I-2, Mg I-2 and Na I-1 are also present, together with the contributions from atmospheric nitrogen bands in the red region of the spectrum.

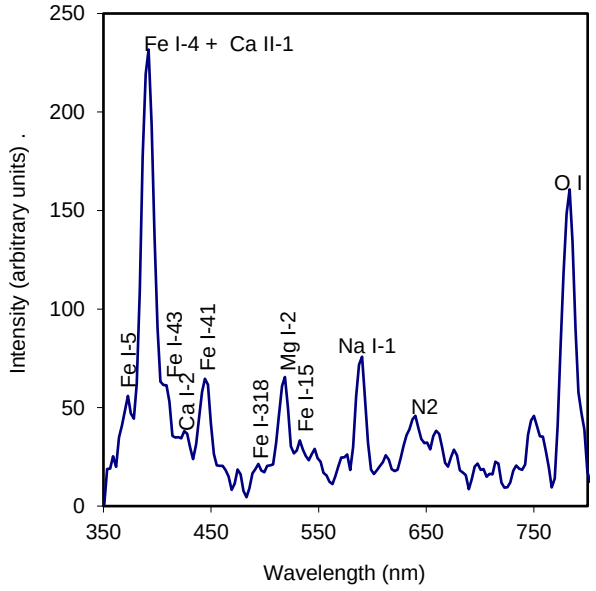

Figure 14 – Calibrated emission spectrum of the SWEMN20210812_215832 fireball.

7 The 2021 August 18 fireball

The bright meteor observed on the 18th of this month was detected at $0^h20^m16.2 \pm 0.1^s$ UTC, and reached a peak absolute magnitude of -9 ± 1 (*Figure 15*). The bolide was recorded from the SWEMN meteor-observing stations located at La Hita, La Sagra, Calar Alto, Sevilla, El Arenosillo, and Sierra Nevada. A video showing this fireball was uploaded to YouTube[20]. It was included in the SWEMN meteor database with the code SWEMN20210818_002016.

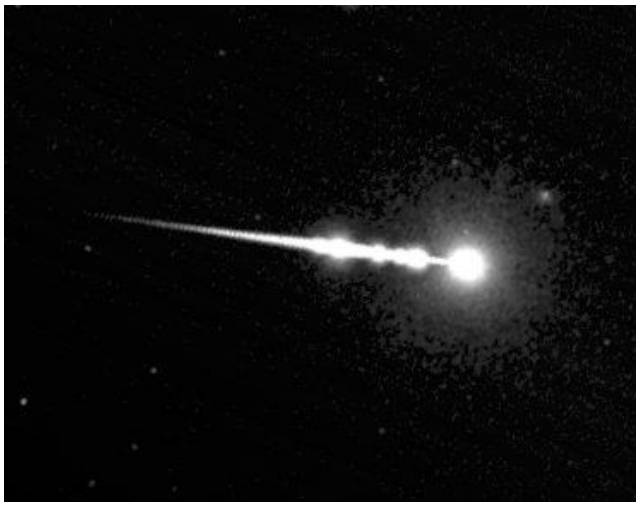

Figure 15 – Stacked image of the SWEMN20210818_002016 "Pajaroncillo" fireball as recorded from La Hita Observatory.

Atmospheric path, radiant and orbit

According to our analysis, the meteoroid hit the atmosphere with an initial velocity $v_\infty = 24.6 \pm 0.3$ km/s, and the apparent radiant of the meteor was located at the equatorial coordinates $\alpha = 293.0^o$, $\delta = +52.3^o$. The fireball began at an altitude $H_b = 103.5 \pm 0.5$ km over the east of the province of Cuenca (region of Castilla-La Mancha), moved southeast, and ended over the same province, at a height $H_e = 67.5 \pm 0.5$ km. This meteor had its initial phase near from the vertical of the village of Pajaroncillo, and for this reason we named it after this place. *Figure 16* shows its atmospheric trajectory and the projection on the ground of this path.

Table 5 – Orbital data (J2000) of the progenitor meteoroid of the SWEMN20210818_002016 "Pajaroncillo" fireball.

a (AU)	2.9 ± 0.1	ω (º)	205.6 ± 0.1
e	0.66 ± 0.01	Ω (º)	$145.00469 \pm 10\text{-}5$
q (AU)	0.9724 ± 0.0002	i (º)	34.2 ± 0.3

From the analysis of the videos recorded for this bolide, we derived the values listed in *Table 5* for the orbital elements of the parent meteoroid. This orbit is plotted in *Figure 17*. The calculated value of the geocentric velocity of this particle yields $v_g = 22.1 \pm 0.3$ km/s. According to the information found in the IAU meteor database, our results show that the fireball was a κ-Cygnid (KCG#0012). This minor meteoroid stream produces every year a display of meteors peaking around August 18 (Jenniskens et al., 2016). So, this event was recorded during the maximum of this meteor shower. The Tisserand parameter with respect to Jupiter yields $T_J = 2.7$, which shows that this meteoroid followed a cometary orbit (JFC type) before entering our atmosphere.

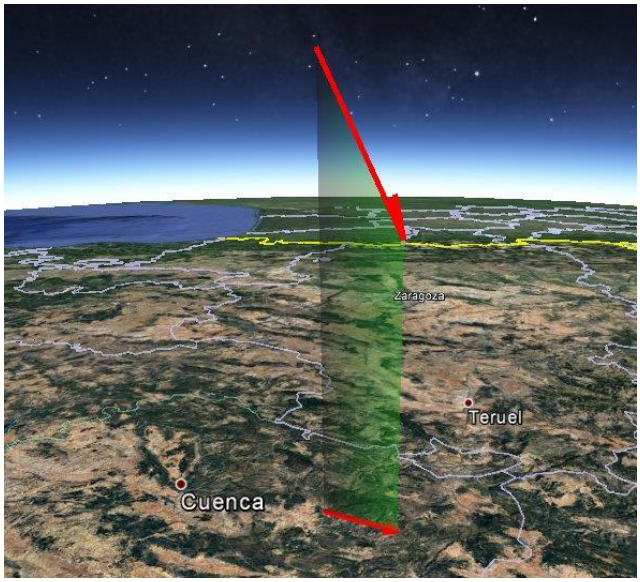

Figure 16 – Atmospheric path and projection on the ground of the trajectory of the SWEMN20210818_002016 fireball.

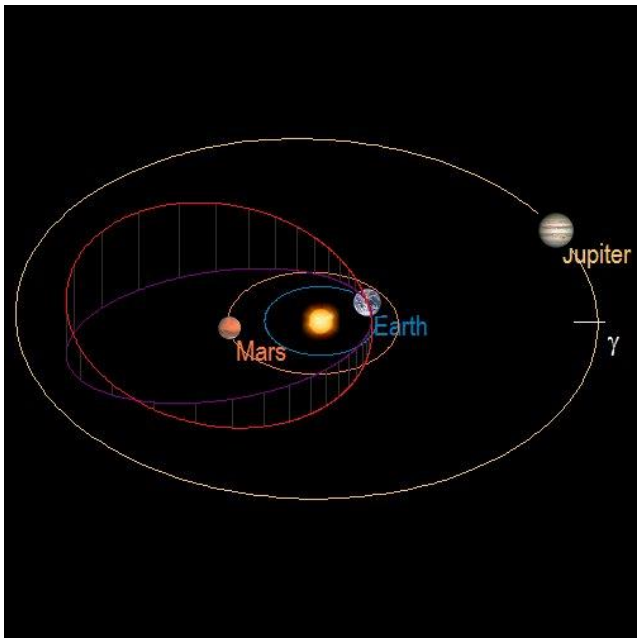

Figure 17 – Up: orbit (red line) of the parent meteoroid of the SWEMN20210818_002016 fireball, and its projection (violet line) on the ecliptic plane.

Emission spectrum

The spectrum of this κ-Cygnid was recorded by our spectrographs located at La Hita Observatory. *Figure 18* shows the calibrated signal, together with the most important emissions. As can be noticed, we have identified lines produced by several Fe I multiplets, as those of Fe I-23, Fe I-21, Fe I-4, Fe I-318 and Fe I-15. The most

[20] https://youtu.be/K3Y_kVikgPE

noticeable contributions to this spectrum are those of Na I-1, Mg I-2, and Fe I-4.

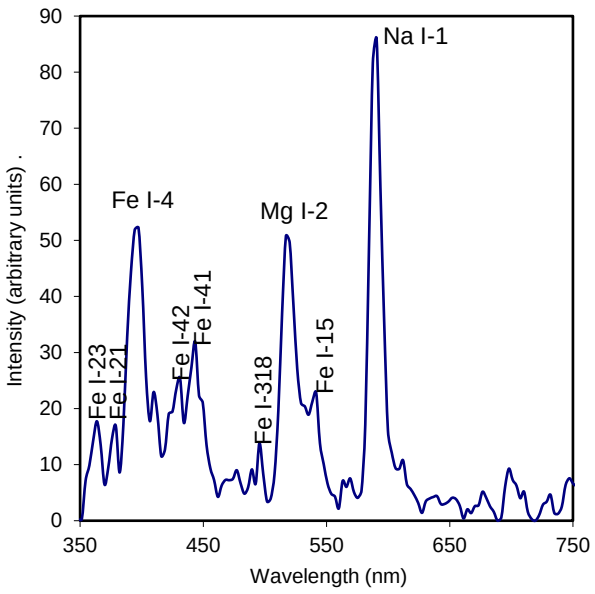

Figure 18 – Calibrated emission spectrum of the SWEMN20210818_002016 fireball.

A deeper analysis of this spectrum will be performed in order to obtain information about the composition of meteoroids in the κ-Cygnid stream. This will be compared with the information obtained previously in the framework of the SMART project for these meteoroids (Madiedo 2015a).

8 Conclusions

We have presented here the most remarkable bolides recorded during August 2021 in the framework of the Southwestern Europe Meteor Network (SWEMN). The absolute peak magnitude of these events ranged from –8 to –12. Their progenitor meteoroids belonged to the sporadic background, the Perseids, the α-Capricornids, and the κ-Cygnids.

The first relevant event recorded during the above-mentioned period was the "Valdepeñas" fireball, an early Perseid spotted on August 3 that reached a peak absolute magnitude of –8. It was recorded 9 days before the maximum of this meteor shower and overflew the provinces of Ciudad Real and Jaén.

The "Villaricos" fireball, recorded on August 5, overflew the Mediterranean Sea and the province of Almería, and reached a peak absolute magnitude of –12. It was produced by a meteoroid belonging to the α-Capricornid stream (CAP#0001). This bolide was detected four days after the peak of this meteor shower, which is produced by Comet 169P/NEAT. The event exhibited a sudden increase in luminosity at the end of its atmospheric path because of the sudden disruption of the meteoroid.

The "Viveros" bolide, spotted on August 10, overflew the provinces of Ciudad Real and Albacete. Its peak absolute magnitude was –8. The progenitor meteoroid belonged to the sporadic background and followed an asteroidal orbit before hitting the Earth's atmosphere.

Another remarkable Perseid fireball was recorded on August 12, during the activity peak of this meteor shower. With an absolute magnitude of –12, this event was the brightest Perseid spotted over the Iberian Peninsula in 2021. We named this event "Navamorcuende". It overflew the provinces of Segovia, Avila and Toledo. In the spectrum of this meteor we have identified the emissions from Fe I-5, Fe I-43, Fe I-41, Fe I-318 and Fe I-15. The most remarkable lines are those of Fe I-4, Ca II-1, and O I. The emissions from multiplets Ca I-2, Mg I-2 and Na I-1 were also found.

The last fireball presented in this report is a mag. –9 κ-Cygnid recorded on August 18, during the peak of this minor meteor shower. It overflew the province of Cuenca, and the progenitor meteoroid followed a JFC orbit before entering our atmosphere. The most significant contributions found in the emission spectrum of this meteor are those of Na I-1, Mg I-2, and Fe I-4.

Acknowledgment

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