Earthquakes, Solar Activity, and Bright Meteors

Daniele Cataldi[1-2], Gabriele Cataldi[1], Valentino Straser[3]

(1) Radio Emissions Project (I). ltpaobserverproject@gmail.com
(2) LTPA Observer Project (I). daniele77c@hotmail.it
(3) Department of Science and Environment UPKL Brussel (B). valentino.straser@gmail.com

Abstract

In recent decades, the observation of the sky has experienced an exponential growth in amateur astronomical observatories, primarily based on high-sensitivity CCTV cameras capable of capturing the night sky, thereby highlighting the transit of meteors. Within this context, there are actual international networks of observatories capable of providing data on the detection of these luminous appearances. In Italy, one of the most active stations is the LTPA Observer Project, established in 2007, which is equipped to monitor the night sky daily and provide key data on astronomical recordings associated with the passage of meteoric bodies in orbit around the Sun, attracted by Earth's gravitational force. In this realm, the study of these events has led to the emergence of a new investigative technique associated with seismic prediction. The LTPA Observer Project and the Radio Emissions Project, two Italian scientific initiatives for studying visible atmospheric luminous phenomena and seismic precursors, have highlighted the need to understand if sometimes the observation of large fireballs can be associated with the occurrence of strong earthquakes, albeit in a temporal context. This study explores precisely this possibility, namely whether the appearance of large fireballs can be considered a new, previously unknown seismic precursor, and whether this meteoric activity could be linked to solar activity.

Keywords: Meteor, Earthquakes, Astronomy, Seismic Precursors, Eliophisics.

1 - INTRODUCTION

The question we posed is whether the observation of large fireballs could be considered a new candidate for seismic precursor, given the emerging relationship between the frequency of large and bright fireballs, solar activity characterized by an increase in space weather phenomena such as M and X class solar flares.

Meteors originate from meteoroids, which are particles of varying sizes, often coming from comets or asteroids and wandering within the solar system, orbiting the Sun. When a meteoroid approaches a celestial body, like Earth, it enters its atmosphere at high speeds, typically between 11 km/s and 72 km/s. This rapid descent causes extreme heating of the meteoroid and the surrounding air, creating a visible glow. The high speed of the meteoroid leads to the ionization of gases in the atmosphere, creating a luminous trail. The brightness of a meteor depends on the size, composition, and speed of the meteoroid, as well as the atmospheric density.

Meteor, Meteoroid, Meteorite: It is important to distinguish between a meteoroid (the rock fragment in space), a meteor (the luminous phenomenon observed when the meteoroid passes through the atmosphere), and a meteorite (any fragment of the meteoroid that survives its passage through the atmosphere and reaches the Earth's surface). [1]

Meteors are classified based on their brightness. The most common are low-luminosity meteors, followed by fireballs and superbolides, which are rare but extremely bright events. A classification of meteors based on brightness, visual magnitude, velocity, distance, and color is as follows:

Low-Luminosity Meteors (Magnitude +5 and above)

- Visual Magnitude: Greater than +5.
- Speed: Varies from 11 km/s (slow meteors) to 72 km/s (very fast).
- Distance: Several tens of kilometers above the Earth's surface.
- Color: Often not very defined due to low brightness; can vary from white to pale yellow.

Bright Meteors (Magnitude from +2 to +5)

- Visual Magnitude: Between +2 and +5.
- Speed: Generally between 30 km/s and 70 km/s.
- Distance: Typically between 70 and 100 km from the observer.
- Color: More defined, with possible shades of yellow, orange, or green depending on the chemical composition.

Fireballs (Magnitude from -1 to +2)

- Visual Magnitude: Between -1 and +2.
- Speed: Often over 20 km/s.
- Distance: Can appear closer due to their greater brightness.
- Color: Variable; yellow, orange, green, and sometimes blue, influenced by composition.

Bright Fireballs (Magnitude from -5 to -1)

- Visual Magnitude: Between -5 and -1.
- Speed: Similar to fireballs, but can appear faster due to greater brightness.
- Distance: Variable, but often closer to the observer.
- Color: Often vivid and variable, with possible long-lasting trails.

Superbolides (Magnitude lower than -5)

- Visual Magnitude: Lower than -5, can reach up to -20.
- Speed: Extremely fast, can exceed 70 km/s.
- Distance: Can be seen from hundreds of kilometers away.
- Color: Very bright and variable, often accompanied by a strong glow and sometimes audible explosions.

The classification of meteors varies based on their brightness, which is closely related to their size, speed, and chemical composition. Visual magnitude is an important parameter as it determines how easily a meteor can be observed with the naked eye. Speed and distance affect the apparent duration of the light trail in the sky. Finally, the color is an indicator of the meteor's chemical composition; for example, sodium produces a yellow color, while iron tends to give a green tint. [2] [3] [4] [10]

1.2 - Solar Activity and Meteoroids

As is known, solar activity plays a fundamental role in the movement of these particles (meteoroids), this interstellar dust, in which we all are immersed, is affected by the variation in solar activity, that is, by the phenomena generated by the Sun. Among these, the ones that we can consider in this study include the following:

- **Coronal Mass Ejections (CMEs)**: CMEs are enormous ejections of plasma and magnetic field emitted by the Sun, capable of traveling through space at high velocities (even 1,000,000 km/h). When these charged particles interact with meteoroids, they can alter their trajectories, especially if the meteoroids are of small size and/or have low mass. [5][7]
- **Solar Wind**: The solar wind, a continuous flow of charged particles emitted by the Sun, can have a cumulative effect on meteoroids over time. This can gradually alter their orbits, especially in relation to smaller bodies. [6]

- **Yarkovsky and YORP Effects**: For larger bodies, thermal effects like the Yarkovsky effect and YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) can play a significant role. These effects are influenced by solar radiation and can cause changes in the rotation and orbit of celestial bodies. [9]
- **Interaction with the Earth's Magnetic Field**: As meteoroids approach Earth, they can also interact with the Earth's magnetic field, which in turn is influenced by solar activity, particularly during geomagnetic disturbance events. [8]
- **Impact on Space Weather Events**: Space weather events, such as geomagnetic storms, can influence the intensity and direction of the solar wind and CMEs, thus further affecting the trajectories of meteoroids. These interactions illustrate the complex dynamics between solar activity and meteoroids, highlighting the importance of studying these relationships to understand better the movement and behavior of these particles in space. [7]

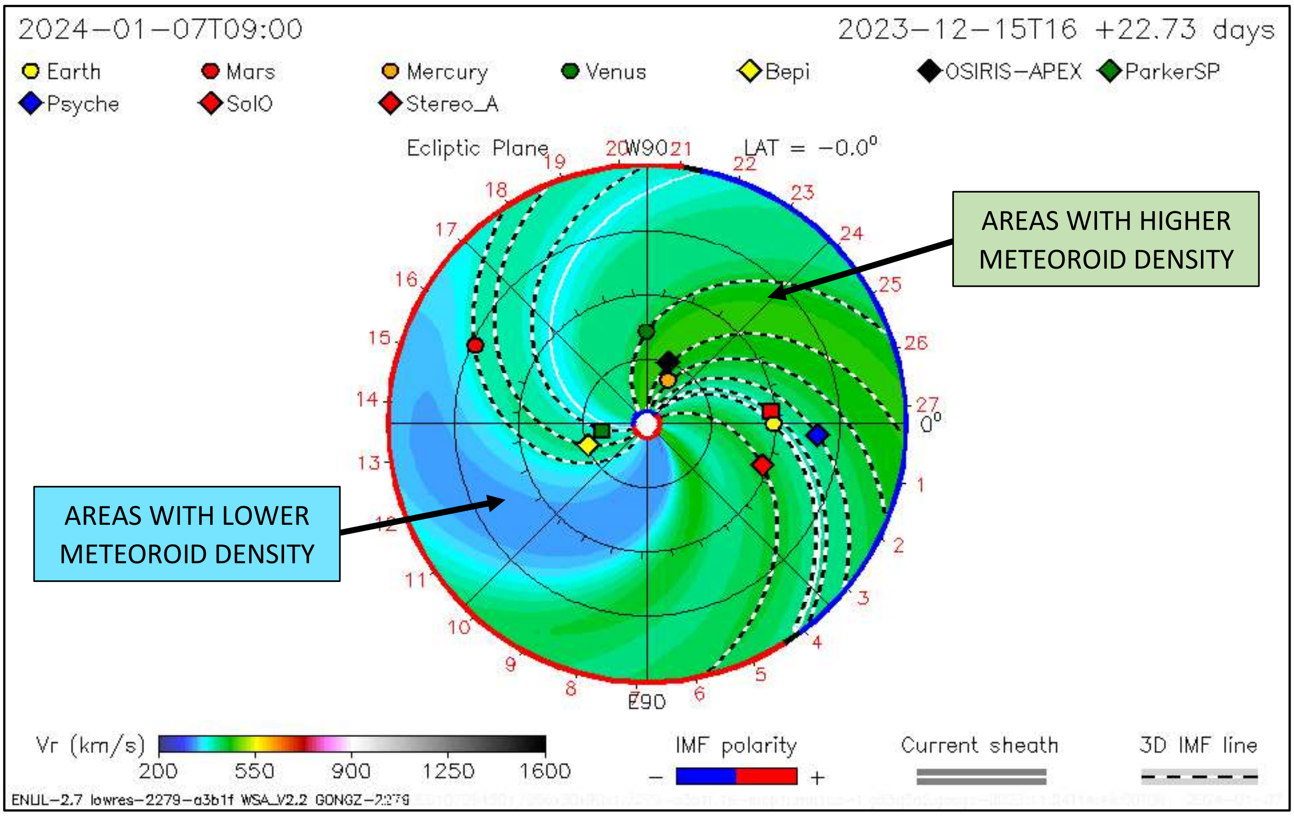

Fig. 1 – Graph showing the velocity of the solar wind. At the center is the Sun, and around it are the various nearest planets, along with the positions of various space probes. Credits: iSWA.

Therefore, as can be understood, this interstellar dust present within the solar system is subject to the flow of the solar wind and the action of shock waves that the sun creates through Flares and CMEs, effectively drawing this dust closer to the planets. This is because the solar wind originates from the Sun and radiates outward from the star, reaching the planets. In this interlude, solar activity moves a mass of dust, the density of which is directly proportional to the extent of the solar activity.

A CME of enormous proportions and speed can carry with it more dust, compared to a CME of lesser magnitude. These characteristics related to solar activity, mentioned so far, are the basis of the hypothesis advanced by researchers engaged in this study.

As visible in Fig. 1, the speed of the solar wind varies with the solar activity itself; there are thus areas in space where the speed of the solar wind is greater compared to other areas, or vice versa, in reference to the presence of sunspots, coronal holes, and general phenomena on the solar chromosphere.

1.3 - L'LTPA Observer Project

In the course of studying space weather, the LTPA Observer Project, based in Italy, has since 2008, begun recording the passage of meteors over Italian territory (central Italy) using a CCTV camera with a sensitivity range between 0.00001 and 0.00045 lux (in Full Time Color), sufficient to observe in color not only the light of the stars but also all astronomical phenomena visible to the naked eye, including the passage of meteors. This CCTV camera is defined as a “Starlight Camera”.

Over the years, it has detected a series of extremely luminous meteoric phenomena, determined by the passage of meteorites of a certain size, capable of illuminating the sky, fragmenting, and in some cases falling to the ground.

From 2008 to the present, this CCTV Camera has operated for over 70,450 hours for its sky surveillance work.

This recording system has also required over 5,870 hours of processing the recorded images, sufficient to catalog the types of phenomena recorded over the years.

This system was the first in Italy to use such sensitive equipment to detect LTPAs or Luminous Transient Phenomena in the Atmosphere, the whole series of luminous phenomena that occur in the Earth's atmosphere, including bright meteors.

An example of such recordings is that of July 21, 2011, when at 01:57 local time, the optical detection station, located in Lariano, Rome, Italy, recorded the passage of a large fireball (Fig. 2).

In this case, the system highlighted its passage, detecting the luminous trail. Another example is that of August 12, 2011, when at 22:29 local time, the optical station located in Lariano, Rome, Italy, recorded the passage of a large fireball (Fig. 3).

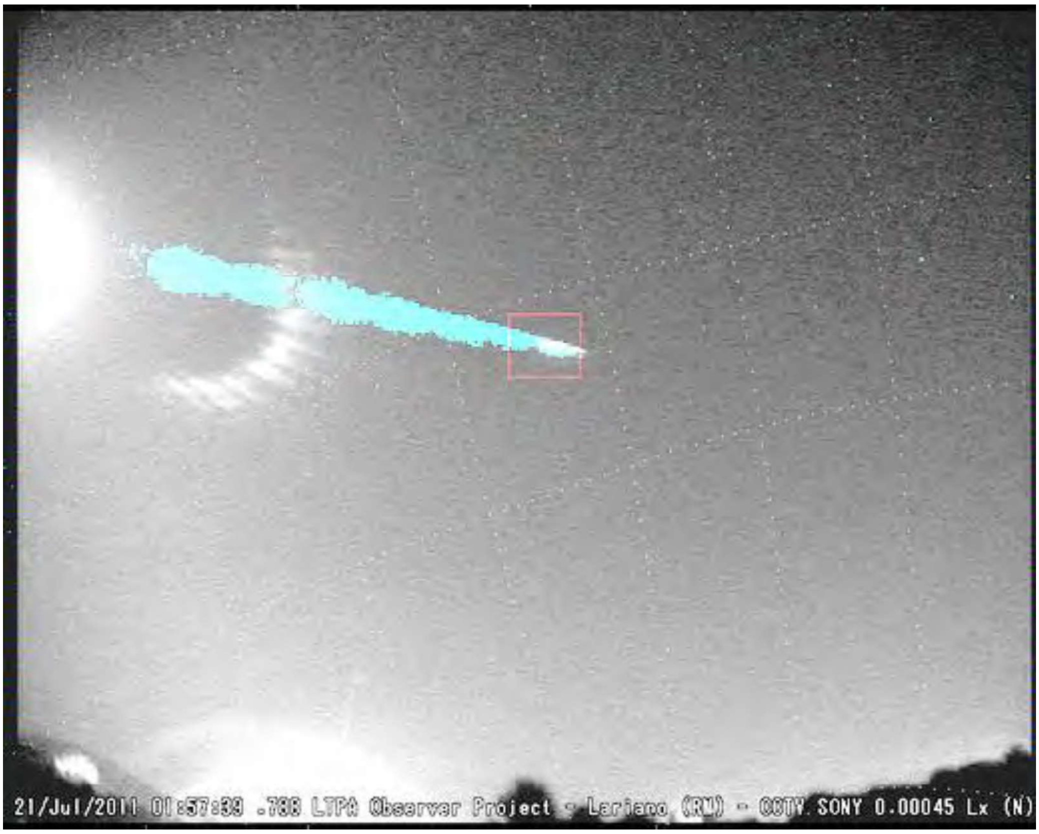

Fig. 2 *– Bright fireball recorded by the optical monitoring station of the LTPA Observer Project, located in Lariano, Rome, Italy. Credits: Daniele Cataldi; LTPA Observer Project.*

***Fig. 3** – Bright fireball recorded by the optical monitoring station of the LTPA Observer Project, situated in Lariano, Rome, Italy. Credits: Daniele Cataldi; LTPA Observer Project.*

The most intense event ever recorded by the station in February was that of February 12, 2011, at 23:34 local time, when a superbolide entered the Earth's atmosphere, illuminating the entire Tyrrhenian area.

The last two frames recorded even show the saturation of the CCD sensor of the CCTV camera, caused by the high intensity of the light flash produced by the impact between the meteoroid and the Earth's atmosphere at an altitude of 80 km (Fig. 4). In this case, the visual magnitude was calculated to be -18.

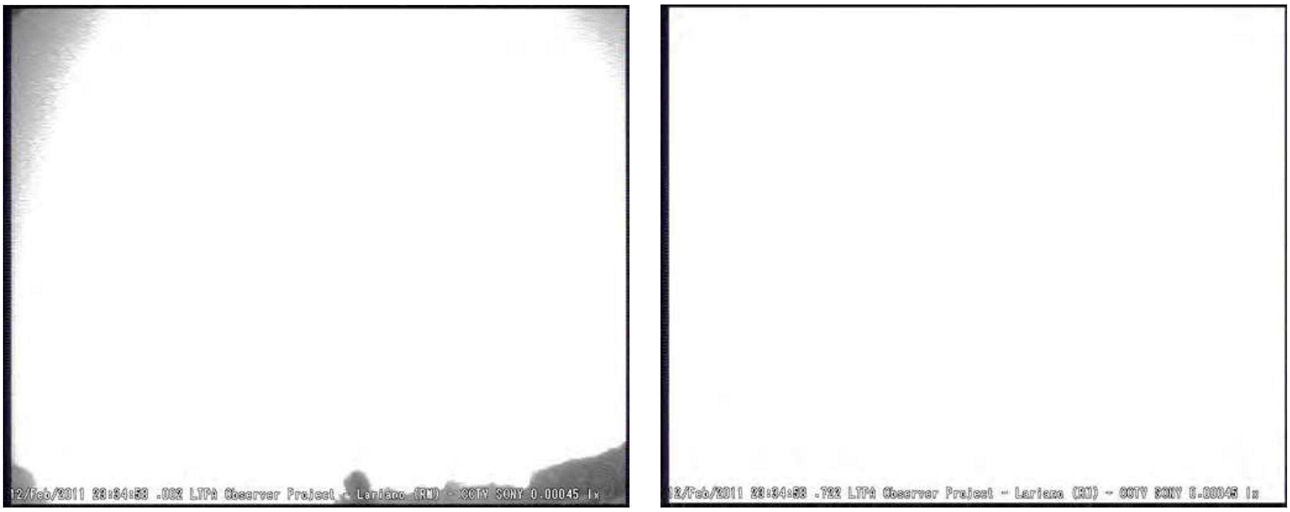

***Fig. 4** – Optical station of the LTPA Observer Project, in Lariano, Rome, Italy, where the recording of the passage of a superbolide, recorded on February 12, 2011, is highlighted. Credits: Daniele Cataldi; LTPA Observer Project.*

The event was subsequently highlighted by various national and international associations and entities, given the exceptional nature of the recording, which had never occurred before in Italy.

2 - METHOD AND DATA

The study conducted by the researchers documented the appearances of large and bright meteors or fireballs on a global scale, limiting the research to large fireballs with a magnitude not exceeding -5.

Similarly, these data were overlaid with solar activity data, namely the count of class M and X Flares that occurred in the same time period, and the global seismic activity of M6+.

The time period covered by the graph, based on the provided data, spans from April 2022 to December 2023. Here is a clarification of the time limits:

- Start: The first event in the graph is a class X solar flare that occurred on April 20, 2022.
- End: The last event in the graph is a class X solar flare that occurred on December 14, 2023.

Therefore, the graph represents a period of approximately 1 year and 8 months, showing the sighting of meteors and the class M and X solar flares that occurred during this time frame. The appearances of the fireballs were obtained through web research on the most important sites for this type of phenomenon.

The retrieval of data related to the passages of luminescent meteors across the sky has been significant and very challenging since typically, these types of appearances last only a few seconds and are not recorded.

2.1 – Meteor and Solar Flares

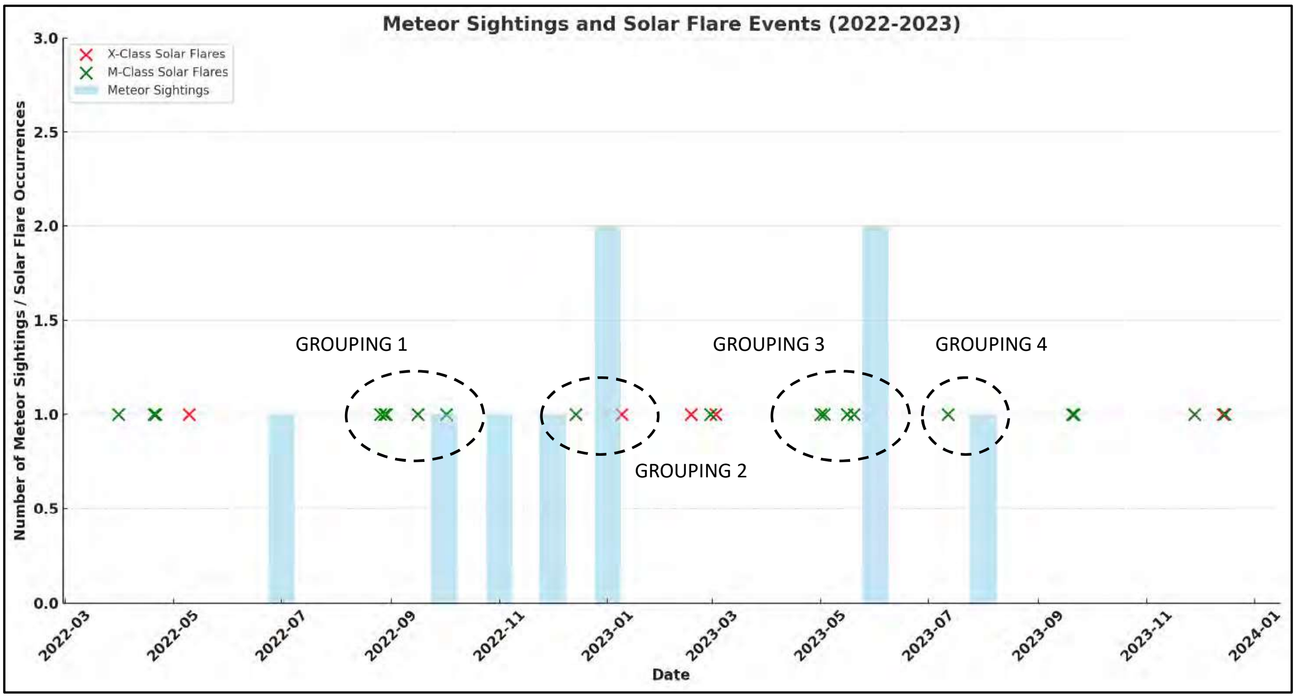

Fig. 5 – Graph showing the trend of solar activity (class M and X Flares) and the appearance of large and bright meteors (Fireballs), observed on a global scale. Credist: iSWA; LTPA Observer Project; International Meteor Organization (IMO); NASA's Meteoroid Environment Office (MEO); European Fireball Network; Global Fireball Observatory (GFO).

Only some of these passages are recorded by the numerous amateur observatories, so the data available to researchers do not include every appearance that occurred, but only those that have been possible to document.

In some cases, the data refer to those reported by a larger number of people, even if not captured by cameras or sensors for detecting this kind of astronomical phenomena. The documentation visible in Fig. 2, 3, and 4 demonstrates that it is possible to detect and study such phenomena and that they are more frequent than one might normally believe.

2.2 – Seismic Events

An important element for this study was to understand when the phenomenon of the appearance of large fireballs could be related to the occurrence of earthquakes on a global scale, that is, whether there existed a second relationship between observing large fireballs and the occurrence of destructive earthquakes with a magnitude of M6+.

The researchers engaged in this study gathered the number of earthquakes that occurred within the same time period in which the large fireballs and class M and X Flares appeared (Source: USGS):

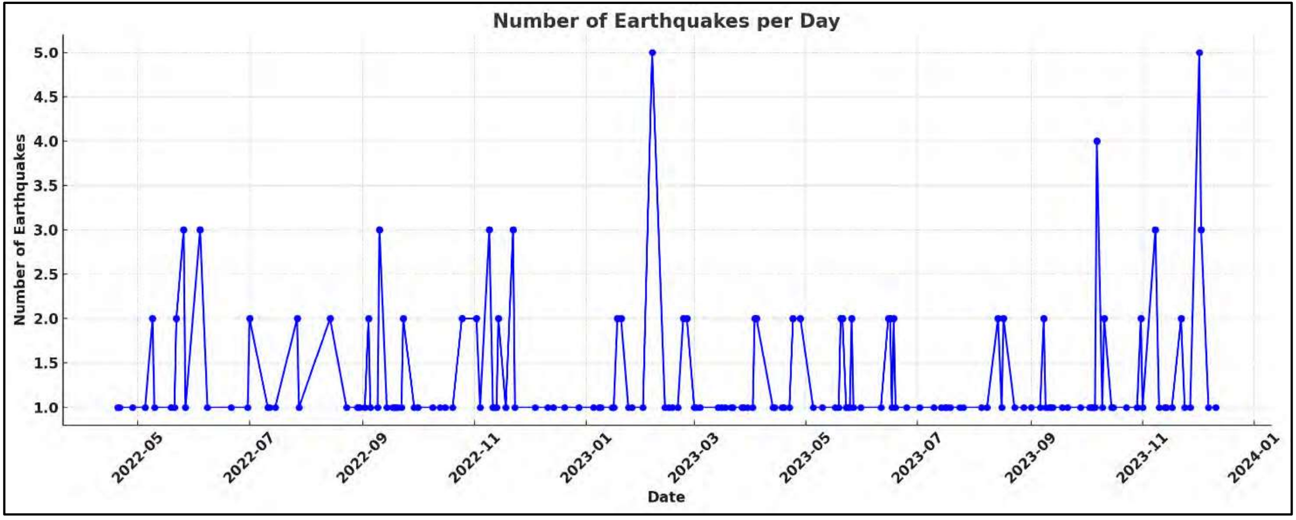

Fig. 6 – Number of earthquakes that occurred between 20 April 2022 and 14 December 2023, on a global scale and with magnitude M6+. Credits: USGS.

As can be seen in Fig. 6, there were many earthquakes with magnitude M6+, on a global scale, in the same calculated time frame, i.e. between 20 April 2022 and 14 December 2023.

The next step was to superimpose this graph on the number of meteors observed and the number of class M and X Flares observed in the same period of time (Fig. 7).

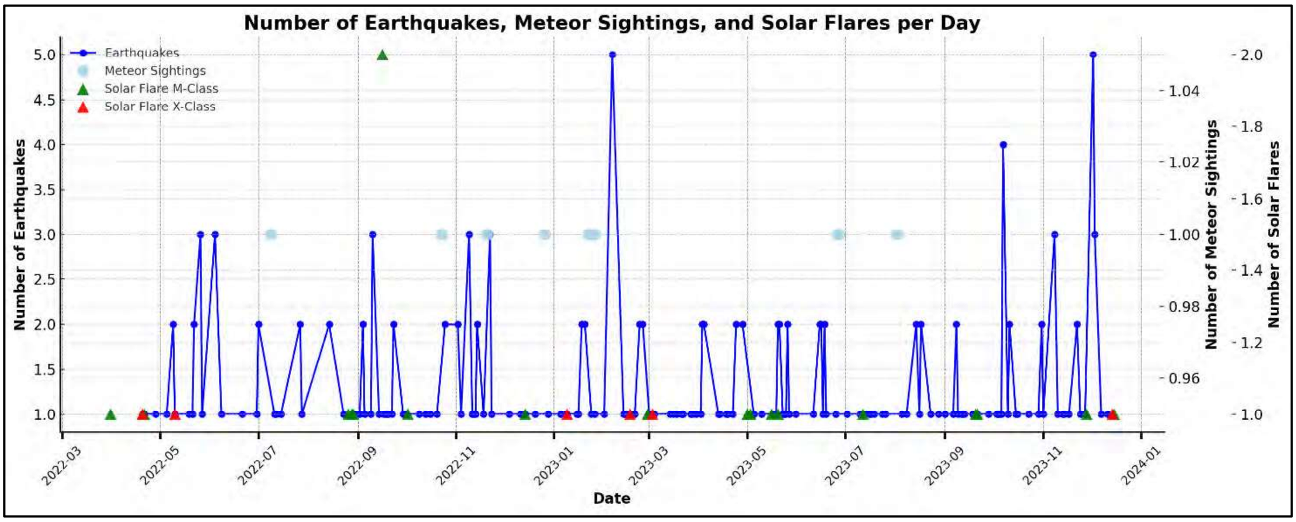

Fig. 7 – Number of M6+ earthquakes, number of M and X class solar flares and number of large bolides observed on a global scale. Credits: LTPA Observer Project, USGS, International Meteor Organization (IMO); NASA's Meteoroid Environment Office (MEO); European Fireball Network; Global Fireball Observatory (GFO); iSWA.

3 - DISCUSSION

Solar activity generates shock fronts whose speed can reach the Earth in 3 days, traveling at approximately (2,077,748 km/h) 577.15 km per second. If we calculate that medium-sized meteors travel at around 72 km/s we can understand that solar activity creates areas of space in which an enormous acceleration is provided to meteoric bodies (meteoroids), of around 8.2 times compared to their speed. This implies that in certain areas of the space between the Earth and the Sun, there are greater quantities of rocky bodies (dust in which meteoroids are found), as visible in Fig. 1, and that these areas, in which there are greater fragments in motion, they approach the Earth at greater speed.

After acquiring the data, distributing them temporally for a duration of 20 months (1 year and 8 months), relationships were sought between the appearance of individual meteors and solar flares. The result is shown in Fig. 5, where small groupings of Flares (Greater solar activity) and the appearance of the brightest meteors are highlighted. The data collected in the graph are the following (source USGS; NASA's Meteoroid Environment Office (MEO); European Fireball Network; Global Fireball Observatory (GFO):

Meteorite Sightings (Real Data)

- Nottingham, England (9 July 2022).
- Wisconsin, USA (23 October 2022).
- Tennessee and Kentucky, USA (20 November 2022).
- Adelaide, Australia (26 December 2022).
- South Yorkshire, England (22 January 2023).
- Cabo Rojo, Puerto Rico (January 26, 2023).
- Germany (26 June 2023).
- New Zealand (27 June 2023).
- United States (August 2, 2023).

Class X Solar Flares (2022 - 2023)

- X2.25: April 20, 2022.
- X1.5: May 10, 2022.
- X2.87: December 14, 2023.
- X2.2: February 17, 2023.
- X2.07: March 3, 2023.
- X1.9: January 9, 2023.

M-Class Solar Flares (2022 - 2023)

- M9.7: April 21, 2022.
- M9.67: March 31, 2022.
- M8.77: October 2, 2022.
- M8.6: August 29, 2022.
- M7.9: September 16, 2022.
- M7.29: April 20, 2022.
- M7.2: August 26, 2022.
- M6.7: August 28, 2022.
- M6.3: December 14, 2022.
- M6.2: September 16, 2022.
- M9.82: November 28, 2023.
- M9.62: May 16, 2023.
- M8.96: May 20, 2023.
- M8.72: September 21, 2023.
- M8.62: February 28, 2023.
- M8.23: September 20, 2023.
- M7.2: May 3, 2023.
- M7.1: May 1, 2023.
- M6.97: December 15, 2023.
- M6.97: July 12, 2023.

As it is possible to understand, the appearances of large fireballs (meteors) are not very frequent, but in any case there are a total of 9. There were 5 class X Flares that occurred on the Sun, and 20 were M class Flares. The graph (Fig 5) show:

- **Grouping 1**: between the end of August 2022 and October 2022 there was a large fireball sighted, preceded by a Series of M-class Flares.
- **Grouping 2**: another interesting grouping is that between December 2022 and January 2023, when a class
- **Grouping 3**: the presence of numerous M-class Flares was highlighted, followed by the appearance of two large meteors (May 2023 – June 2023).
- **Grouping 4**: the presence of a class M Flare in the local vicinity of a luminous fireball between July 2023 and August 2023 is highlighted.

It is evident that most of the bright meteors appeared close (temporally) to a grouping of solar flares.

Other important data are the seismic data relating to the same time period, i.e. all the M6+ earthquakes that occurred on a global scale.

The researchers' study focused on verifying whether there could be a relationship between all these phenomena; in the past, a clear relationship between earthquakes and solar phenomena has already been observed [11] [12] [13] [14] [15], in this case it was possible to ascertain this relationship again by observing Fig. 7 where the number of M6+ earthquakes, the number of M and X class solar flares, and the number of appearance of large fireballs are visible.

For the first time ever this study shows what was previously a hypothesis of the researchers and which in this case the data confirmed, that is, that the number of large fireballs follows the groupings of earthquakes, especially those with the greatest number of cases occurring in short time.

In addition to this, it is highlighted that the Flares are always associated with the presence of strong earthquakes and in this case, again as already described for Fig. 5, there is a clear relationship between the number of large fireballs spotted and solar activity.

4 - CONCLUSION

It is concluded that, at least on a hypothesis level but supported by data, solar activity can be associated with the occurrence of M6+ earthquakes on a global scale.

Solar activity, in this context, plays an important role in bringing interstellar dust, in which fragments of more or less large rocks move, closer to celestial bodies such as the Earth.

In particular, the number of luminous fireballs with a magnitude no lower than -5 in brightness, analyzed in this study, is linked to solar activity and earthquakes.

Solar activity also appears to interact on the orbits of larger fragments, which are usually less susceptible to variations in their orbit than smaller fragments.

This could explain the existence of a direct relationship between the appearance of large meteors and intense solar activity. More evident, however, seems to be the relationship between solar activity and earthquakes, summarized in Fig. 7, while at present the relationship between solar activity and meteoric phenomena is less evident, if referred to the analysis of events lasting 1 year and 8 months.

REFERENCES

[1] Коротышкин Д.В., Шерстюков О.Н., Валиуллин Ф.С. - Meteor observations at the radar station of Kazan Federal University - INASAN Science Reports. Vol 8(6). M.: Janus-K, 2023, 58 pp. - DOI: 10.51194/INASAN.2023.8.6.002 - ISSN 2658-5669 e-ISSN 2712-8318

[2] V.´ı. Porubcan, M. Bucek, G. Cevolani, P. Zigo. Variation of Meteor Heights and Solar-Cycle Activity - PASJ: Publ. Astron. Soc. Japan 64, 86, 2012 August 25 (C) 2012. Astronomical Society of Japan - (Received 2011 December 9; accepted 2012 February 24). DOI: 10.1093/pasj/64.4.86.

[3] P. Matlovič, J. Tóth. Meteors: Light from Comets and Asteroids - 2019 - Computational Structural Engineering Institute of Korea - Online ISSN: 2287-2302 - Print ISSN: 1229-3059 - DOI: 10.7734/COSEIK.2019.32.2.133.

[4] S. Feng, R. Wang. Meteoroid and Space Debris Risk Assessment for Satellites Orbiting the Earth/Moon - Received: Nov 3, 2022 Accepted: Jun 25, 2023 Published: Sep 19, 2023 - Chinese Journal of Space Science, Volume 43, Issue 4: 724 - 735 (2023) - DOI: 10.11728/cjss2023.04.2022-0065.

[5] S. E. Gibson, U. Bąk-Stęślicka, R. Casini, J. Dahlin, E. DeLuca, G. de Toma, Y. Fan, J. Karpen, L. A. Rachmeler, S. Tomczyk, A. Caspi, B. Chen, M. Corchado-Albelo, S. Farid, N. Karna, T. Kucera, A. Paraschiv, N. E. Raouafi, T. Schad, D. Seaton, S. Begum Shaik, M. L. Wilson, J. Zhang. Coronal Polarimetry: Determining the Magnetic Origins of Coronal Mass Ejections - 2023 - Heliophysics 2024 Decadal Whitepapers- Vol. 55, Issue 3 - DOI: 10.3847/25c2cfeb.8528ec7b.

[6] R. Reda, M. Stumpo, L. Giovannelli, T. Alberti, G. Consolini. Disentangling. the solar activity–solar wind predictive causality at Space Climate scales - 2024 - Frontiers in Italian studies on Space Weather and Space Climat - DOI: 10.1007/s12210-023-01213-w.

[7] H. Raju, S. Das. Interpretable ML-Based Forecasting of CMEs Associated with Flares - 2023 - Solar Physics - 298(8) - DOI: 10.1007/s11207-023-02187-6.

[8] C.D. Watkins, R. Eames, T.F. Nicholson. Further studies of the effect of the Earth's magnetic field on meteor trains - Journal of Atmospheric and Solar-Terrestrial Physics - Elsevier BV - 33(12):1907–1921 - DOI: 10.1016/0021-9169(71)90167-X.

[9] F. Marzari, A. Rossi, O. Golubov, D. J. Scheeres. Evolution of an Asteroid Family under YORP, Yarkovsky, and Collisions - The Astronomical Journal - Published 2020 August 21 © 2020 - DOI 10.3847/1538-3881/aba7be.

[10] R. Sennlaub, M. Hofmann, M. Hankey, M. Ennes, T. M Uller, P. Kroll, P. Mader. Patrick MäderPatrick Mäder. Object classification on video data of meteors and meteor-like phenomena: algorithm and data - Monthly Notices of the Royal Astronomical Society - Published by Oxford - University Press - Print ISSN: 0035-8711 - DOI: 10.1093/mnras/stac1948.

[11] V. Straser, G. Cataldi. 2014. Solar wind proton density increase and geomagnetic background anomalies before strong M6+ earthquakes. Space Research Institute of Moscow, Russian Academy of Sciences, MSS-14. Moscow, Russia – 2014.

[12] G. Cataldi, D Cataldi, V. Straser. Solar wind proton density variations that preceded the M6+ earthquakes occurring on a global scale between 17 and 20 April 2014. European Geosciences Union (EGU) General Assembly 2015, Natural Hazard Section (NH5.1), Sea & Ocean Hazard - Tsunami, Geophysical Research Abstract, Vol. 17, Vienna, Austria. Harvard-Smithsonian Center for Astrophysics, High Energy Astrophysics Division, SAO/NASA Astrophysics Data System.

[13] G. Cataldi, D. Cataldi, V. Straser. Solar wind proton density variations that preceded the M6,1 earthquake occurred in New Caledonia on November 10, 2014. European Geosciences Union (EGU) General Assembly 2015, Natural Hazard Section (NH5.1), Sea & Ocean Hazard - Tsunami, Geophysical Research Abstract, Vol. 17, Vienna, Austria. Harvard-Smithsonian Center for Astrophysics, High Energy Astrophysics Division, SAO/NASA Astrophysics Data System.

[14] G. Cataldi, D. Cataldi, V. Straser. Solar activity correlated to the M7.0 Japan earthquake occurred on April 15, 2016. New Concepts in Global Tectonics (NCGT) Journal, Vol. 4, No 1, 2016, Australia.

[15] G. Cataldi, D. Cataldi, V. Straser. Solar and Geomagnetic Activity Variations Correlated to Italian M6+ Earthquakes Occurred in 2016. European Geosciences Union (EGU) General Assembly 2017. Seismology (SM1.2)/Natural Hazards (NH4.7)/Tectonics & Structural Geology (TS5.5) The 2016 Central Italy Seismic sequence: overview of data analyses and source models. Geophysical Research Abstracts Vol. 19, EGU2017-3681, 2017.