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A NEW PROPOSAL OF THE TERM METEOROID

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ABSTRACT

In this document we briefly review the evolution of the term meteoroid and we make several proposals for a definition, emphasizing the importance of the criteria used for it. Finally, we propose a definition based on observations rather than on the instrument of observation.

RESUMEN

En este documento realizamos una breve reseña de la evolución del término meteoroide y hacemos varias propuestas para una definición enfatizando la importancia de los criterios empleados para ello. Finalmente proponemos una definición basada en observaciones más que en el instrumento de observación

Key Words: meteorites, meteors, meteoroids — minor planets, asteroids: general

1. SHORT HISTORICAL EVOLUTION OF THE TERM METEOROID

Since ancient times, humanity has observed the sky discovering countless bodies that inhabit the vicinity of the Earth and beyond. From the Egyptians to the Greeks and the civilizations of the East, the passage of "shooting stars" or "meteors" through the sky was captured in their writings and/or records [e.g. Yang et al. (2005)]. Many of these discoveries are currently linked to the smaller bodies that are part of the Solar System and/or to those bodies that cross the interplanetary medium by approaching or interacting with the Earth. Such bodies are what we recognize and study now as asteroids and comets (Marvin 1996; Williams 2002, 2011). The former range from the structure known as the asteroid belt and the conglomerates in the vicinity of our planet known as the Aton, Apollo, Amor and Atira families, to the groups that exist in the Jovian or Trans-Neptunian regions, while the latter, from the Kuiper Belt or the Oort Cloud, cross the interplanetary medium leaving behind a trail of rocks and dust. Asteroids and comets are linked to bodies that reach Earth or that intercept its orbit; in some cases, they can not only cross the Earth's atmosphere but also impact the surface of our planet or settle at the bottom of the sea. The observation of bodies that come from space has been documented in many research works, and since the 19th century the observations carried out of the phenomena called "shooting stars" were collected in works such as those of Herschel (1802) and Newton (1865). Before the nineties of the 20th century a difference had already been established between asteroids and bodies that travel in space, which were given the name of meteoroids.

This last term was coined by Millman (1961) to differentiate these bodies from each other on the basis that asteroids were bodies larger than 100 meters. According with Millman (1961) a meteoroid could be defined as a solid body travelling in the interplanetary medium of a size much smaller than an asteroid but much larger than an atom or molecule. For many years this definition worked well, but it was not until the end of the last century that the scientific community started to analyze the meteoroid concept not only as to the body size but also as to the phenomena produced by these bodies when they cross the terrestrial atmosphere.

Along with the definition for asteroid and meteoroid, in 1961 the definitions for meteor, fireball and micrometeorite were also established. These definitions, approved by the IAU were: (a) Meteorite: body that has reached the surface of the Earth without being completely evaporated. (b) Meteoroid: solid body that moves in the interplanetary medium with a size considerably smaller than that of an asteroid but considerably larger than that of an atom or molecule. (c) Meteor: luminous phenomenon that occurs when a particle from space enters the Earth's atmosphere. (d) Fireball: bright meteor with a luminosity equal to or greater than the brightness of the

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planets. (e) Micrometeorite: very small meteorite or particular meteorite with a diameter of less than one millimeter.

By 1990, the discovery of the asteroid 1990UN, which has a diameter of 100 meters and an absolute magnitude greater than 23 ($H > 23$, Borovička 2016), as well as the arrival of a few meter objects to our planet, led to a revaluation of the concept *meteoroid* that was beginning to be obsolete by then; thus, in the last three decades it has become necessary to classify with greater precision the bodies that come from space, attending mainly to their size, although in this century, other parameters have also begun to be considered within the proposed definitions, such as speed, albedo and chemical composition, among others. Thus, since the nineties of the last century, the new definitions that have been proposed have been based on observations made with various techniques and state-of-the-art instruments, and these have been discussed in scientific sessions of the International Astronomical Union (IAU).

In 1995, Beech and Steel proposed a definition based on the size of the object. According to their work, "any solid natural object in space of a cometary or planetary nature, with a size greater than 10 meters could be considered an asteroid or minor planet, while an object much smaller than 10 meters, which could even be cometary in nature, but larger than 100 microns could be defined as a meteoroid". With this definition, a new question arose related to those bodies smaller than 100 microns, based on the phenomenon produced by meteoroids when they enter the Earth's atmosphere which is known as a "meteor". These authors mention that, for a meteor to be produced, the object has to be larger than 100 microns (Bronshten 1981); that is, if the body is larger than 100 microns then we are talking about a meteoroid, but if its size is less than this value then it is a dust particle. The 100 microns barrier represents the frontier between meteoroids and smaller bodies.

With these arguments, the definition that was finally proposed was the following: "a meteoroid is a solid body that moves in space, with a size smaller than 10 meters but larger than 100 microns". The authors also proposed that the definitions of dust and micrometeorite could be modified, which by then had already been discussed in the IAU work sessions being those: (a) Dust: finely divided rocky matter with particle sizes much smaller than the size of a micrometeorite. (b) Micrometeorite: very small meteorite or meteorite particle with a diameter of less than one millimeter.

Even so, Beech & Steel (1995) proposed the following modifications for these last definitions: (a) Dust: Particles that originate or exist in space with sizes much smaller than 100 microns. (b) Micrometeorite: Small meteorite whose size exceeds 100 microns.

While these changes were taken into account, the IAU also considered that the definition of meteorite did not need to be modified under the definition of meteoroid proposed by Beech and Stell (1995), since by then the definition for a meteorite had gone through a long process of modifications (Craig 1849; Rubin & Grossman 2010; Cohen 1894; Farrington 1915; Nininger 1933; Millman 1961; Mason 1962; Gomes & Keil 1980; McSween 1987; Krot et al. 2003). Therefore, by 2003 the definition of a meteorite was established as: a solid body of extraterrestrial material that penetrates the atmosphere and reaches the Earth's surface (Krot et al. 2003). Seven years later, Rubin & Grossman (2010) gave a new version of the concept of meteorite and meteoroid based on the fact that meteorites have also fallen on the Moon and Mars, and small interplanetary objects can impact a spacecraft. These researchers proposed that:

(a) A meteorite is a natural solid body larger than 10 microns and that comes from a celestial body. (b) A meteoroid is a natural solid body that moves in the interplanetary medium and has a size between 10 microns and one meter.

Additionally, these authors provide a definition for micrometeoroid and for micrometeorite, these being the following:

(a) Micrometeoroid: meteoroid with a size between 10 microns and 2 mm. (b) Micrometeorite: meteorite with a size between 10 microns and 2 mm.

Six years after the work of Rubin & Grossman (2010), Borovička (2016) published a work with new and more precise definitions based on physical and astronomical arguments. These new definitions arose as a need to identify the rocky matter that travels in the interplanetary medium and that can impact the Earth's surface. The definitions were born from the discussions carried out by several researchers who were part of Commission 22 of the IAU and are listed below:

(a) Comet: active solid body with a diameter greater than 1 m and smaller than a dwarf planet that moves across, or comes from, the interplanetary medium. (b) Asteroid: non-active solid body with a diameter greater than 1 m and smaller than a dwarf planet that moves across, or comes from, the interplanetary space. (c) Meteorite: solid body that survives the meteor phase as it passes through a gaseous atmosphere without being completely evaporated. (d) Meteoroid: solid body with a diameter between 30 microns and one meter that moves across, or comes from, the interplanetary medium. This body becomes a meteorite when the ablation process stops and the object enters the phase of dark flight towards the Earth's surface. In particular, a meteorite smaller than a millimeter is called a micrometeorite. (e) Meteor: it is referred to light and the associated phenomenon that results from the entry of a solid object from space into a gaseous atmosphere. The phenomenon can be caused by a meteoroid, a comet, an asteroid or any particle with a certain mass, speed and mean free path crossing a planetary atmosphere. This phenomenon can occur in any planet or satellite that has an atmosphere dense enough for the meteoroid to evaporate, totally or partially, as it passes through the atmosphere. Meteors with an absolute magnitude smaller than -4 are called fireballs, while those with an absolute magnitude smaller than -17 are called superbolides. (f) Dust: finely divided rocky matter smaller than the size of meteoroids that moves through the interplanetary medium and can be observed in the zodiacal cloud (Lasue et al. 2020), zodiacal dust lines, and cometary tails. Dust from cometary tails can have sizes that place it in the meteoroid classification. Due to their size, very small dust particles do not produce meteors when they enter a planetary atmosphere, only heat below the melting point, and can reach Earth without being altered. When they are collected in the atmosphere, they are called interplanetary dust particles (IDPs) or Brownlee particles (Brownlee 1985). (g) Meteorite smoke: solid matter that has condensed in the gaseous atmosphere from material that evaporated during the meteor phase. The size of meteorite smoke particles is in the subnanometer range.

In recent years and considering other phenomena such as the YORP effect and the Yarkovsky effect, the above definitions could be modified. In this paper we propose a new definition for the term meteoroid based on both physical effects.

2. THE IMPORTANCE OF THE CRITERIA

In the class "Introduction to Space Physics" at the Sciences Faculty at UNAM, I (Cordero-Tercero) show to my students a slide with several little animals: ladybug, mantis, butterfly, centipede, stick insect, snail, and spider; and I ask them how many insects do they see. I get several answers, but when I tell them that an insect is a small invertebrate animal that has six legs and generally one or two pairs of wings, they answer correctly. After that we discuss the importance of a definition and the criteria to adopt it. To exemplify, we discuss the definition of a planet expressed in Resolution 5 of the General Assembly of the IAU in 2006. From our point of view, this definition does not consider small planetary bodies as important, only as points moving around the Sun's gravitational force. The definition may not please many, but it is adequate according to a dynamic criterion. However, from the point of view of geology, geophysics or astrobiology, they are indeed important. In the next sections, we propose several definitions of the term *meteoroid* based on an equal number of criteria. Several of them have been discussed by the scientific community, and we only collect them here. We are conscious that the definition proposed by Commission 22 of the IAU is valuable and that it was result of hard work. However we consider that we can show another valid point of view.

3. PROPOSED DEFINITIONS

In this section, we propose several criteria to define the term *meteoroid* and analyse their advantages and disadvantages.

3.1. *About the Lower Limit to Define a Meteoroid*

Another example of the difficulty in agreeing on the way in which an object is defined is the dust. According to Mann et al. (2014) the terminology used to refer to dust comes from the different ways that it is studied; thus, the dust size has a wide range and includes meteors, meteoroids, meteoric smoke, meteorites, IDPs, zodiacal dust particles and β-meteoroids. This is strange because in the same category are placed meteors that are light phenomena, objects like meteorites that can be several meters in size, and particles as small as zodiacal dust. On the other hand, Krüger & Grün (2014) say that dust in the Solar System, also called micrometeoroids, are fine particles whose size ranges from a few molecules to tenths of millimeters. These particles are subject to various forces: gravity, radiation pressure, Lorentz force, Poynting-Robertson drag and ion drag. In consonance with these, particles of different sizes (between 0.01 μm and 100 μm), and in all rigor physical properties like their mineralogy, are affected mainly by one or several of these forces.

In our Solar System, particularly in the interplanetary medium, dust particles modify their orbital parameters when they interact with the solar radiation field, absorbing, scattering and re-emitting part of the energy intercepted by the cross section that the small body presents to the radiation flux.

The radiation force that results from such an interaction has two components, the first is a radial force called radiation pressure that points away from the star when the particles are considered to be spherically symmetric; and the second is an azimuthal force known as the Poynting-Robertson effect (P-R drag) which causes dust particles in bounded orbits to spiral towards the Sun as their orbits become circular.

The relationship between the radiation pressure force and the solar gravity force is known as the β parameter and depends only on the properties of the particle (Mignard 1984; Mann 2009)

Paying attention to the wavelength of the energy intercepted by dust, $\beta \approx 1/r$ for $s \gg \lambda$ (where r is the heliocentric distance of the particle from the star, s is the dust particle radius, and λ the wavelength of the incident radiation); $\beta \approx$ constant for particles with $s \ll \lambda$ (Rayleigh limit) i.e. β depends on the size, geometry and chemical composition of the particle as well as on the wavelength of the incident light. When the radiation pressure force is greater than the solar gravity force, the particles with $\beta > 1$ are not bounded and can leave the Solar System describing hyperbolic trajectories. These types of particles are known as β meteoroids (Berg & Grün 1973; Zook & Berg 1975; Burns et al. 1979; Mann 2009), and their dynamics depend on their kinetic energy, orbital angular momentum, and potential energy that the dust particle had at the time it was formed. The maximum value of β corresponds to $s \approx \lambda$.

On the other hand, when $\beta > 1$, dust particles have zero angular momentum, which corresponds to a fictitious case, since as it has been shown by several researchers, β can have very small values that allow a circumsolar orbit to be open (Dohnanyi 1973) and dust particles can be ejected. For dust particles produced by comets, if they are small enough to be disturbed by solar radiation, they will reach any region or point of their orbital plane in relatively short times, moving away from the original orbit of the parent body (comet) due to the direct radiation pressure, or will spiral towards the Sun by the P-R effect (Kresák 1976). In particular, when all the incident radiation does not transfer momentum effectively, β acquires very small values and the orbit described by cometary dust particles will be elliptical or hyperbolic with a new semi-major axis given by:

$$a' = a_0 \; (1-\beta) \; (1-e_0) \; (1-e_0-2\beta)^{-1}, \qquad (1)$$

where a_0 and e_0 are the comet original semi-major axis and eccentricity values, respectively (Kresák 1976). Then, the escape limits of a cometary particle ejected at perihelion β_P and aphelion β_A are, respectively:

$$\beta_P = \frac{1}{2}(1-e_0) \quad \textit{and} \quad \beta_A = \frac{1}{2}(1+e_0). \qquad (2)$$

These equations represent two critical values of β and their magnitude depends on the orbital eccentricity. The values for the cometary particles that come from the Encke comet are: $\beta_P = 0.076$ at perihelion and $\beta_A = 0.924$ at aphelion (Kresák 1976). In the Solar System, most of the Beta meteoroids have values in the interval: $0.5 < \beta < 1$, although the ejected bodies do not reach high speeds and their size is a fraction of microns (Mann 2009).

In recent decades, small bodies and dust have been discovered forming debris disks around stars of spectral types B, A, F, G, K and M (Mann 2009) as well as planets around stars of type G, K and M.

In particular, protoplanetary disks have been detected around the stars β Pictoris, Vega, UA Microscopii (UA Mic) and Fomalhaut. These protoplanetary disks contain large amounts of dust where the ejection process could be occurring. In the case of β Pictoris and its debris disk, the studies indicate that Beta meteoroids can escape with speeds between $\approx$ 50 and 90 km/s, the lowest speed being associated with ice dust, while the highest speed is related to dust particles made up of carbon. Escaping dust particles from β Pictoris have sizes of several microns (Mann 2009). On the other hand, in protoplanetary disks, dust particles that could be influenced by the P-R drag are those for which $\beta \approx 0.5$ which implies that the P-R drag does not affect the evolution of any dust particle in the disk (Wyatt 2009), as is the case of particles that have bounded orbits and whose collision time is shorter than the lifetime related to the P-R drag.

Wyatt (2009) states that there are two types of disks: the dense ones that are dominated by collisions and have few grains under the influence of P-R drag; and the thin disks that are dominated by P-R drag and dust particles in the disk are affected by this drag. The ejection processes, as well as the collisions and the influence of the P-R effect on dust particles, are associated with the star life stage, since in the case of young stars, radiation fluxes and winds are highly variable compared to those of mature stars.

Visible meteors are associated to centimeter-sized objects (Krüger & Grün 2014), but strictly speaking this depends on their velocity, entry angle and composition. This can be a criterion to mark the lower limit of a meteoroid, but according to the previous paragraphs, there could be many criteria to define this lower limit; they will depend on what physical properties of the objects are important and why.

In 2016, Borovička (2016) mentioned that the maximum influx of particles that enter Earth's atmosphere have a size of 100 μm, but considers that a better dust-meteoroid boundary could be 10 μm or even 30 μm. This last value was the chosen as the lower limit to define the term meteoroid according to Commission 22 of the IAU.

3.2. *Yarkovsky and YORP Effects*

The interaction of solar radiation with the surface of bodies smaller than few tens of kilometers (< 30-40 km) (Bottke et al. 2006; Fenucci & Novaković 2021) generates a force able to produce small changes in the asteroids' orbital parameters, moving them away or closer to the Sun depending on their prograde o retrograde rotation (Yarkovsky effect), and torques capable of modifying the spin rates and axis orientations of asteroids (YORP effect, by Yarkovsky-O'Keefe-Radzievskii-Paddack).

The Yarkovsky effect has two components: seasonal and diurnal (the latter commonly larger than the former) that significantly affect asteroids of tens of meters to $\approx$ 10 km (Burbine 2017). Chesley et al. (2003) carried out the first measure of this effect on a planetary object: the asteroid 6489 Golevka, of 530 m diameter. Before, the Yarkovsky effect had been detected only in the motion of artificial satellites (Chesley et al. 2003). Using OSIRIS-REx spacecraft tracking data and a thermophysical model of Bennu, Farnocchia et al. (2021) estimate that Bennu's semi-major axis drifts -284.6 ± 0.2 m/yr. In addition, Greenberg et al. (2020), using optical and radar data of 600 NEAs, made a list of 247 asteroids for which it is possible to quantify the Yarkovsky effect.

The YORP effect has been detected in around nine asteroids (Zegmott et al. 2021). This is important for asteroids of size less than $\approx$ 10 km, and is considered to be the main cause of the spin change of small asteroids (Golubov & Scheeres 2019).

Bottke et al. (2006) and Grieve & Shoemaker (1994) among others, think that the number of near Earth objects has been constant during the last 3 billion years; this means that there must be a mechanism to supply new asteroids into the inner Solar System (to renew those that have impacted with other planetary bodies). Morbidelli & Vokrouhlický (2003) think that impacts between main belt asteroids are not enough to explain the constant number and that the Yarkovsky and YORP effects can help to restock the inner Solar System with asteroids.

Models about the Yarkovsky and YORP effects take into consideration several characteristics of the asteroid, such as diameter, density, thermal conductivity, semi-major axis, heat capacity of the surface, obliquity, rotation period, emissivity and absorption coefficient (e.g. Fenucci & Novaković 2021).

Given the above, we can say that the Yarkovsky and YORP effects are important for the dynamics of asteroids, and that they implicitly provide information about the physical properties of these objects. In this context, we could say that a meteoroid *is an object that is affected by the Yarkovsky and YORP effect.* According to Bottke et al. (2006), the Yarkovsky effect works on objects of sizes between 0.1 m and 40 km, and the YORP effect is important in the variation of the spin rates of main belt asteroids with diameters less than 40 km.

According to the previous paragraphs, we propose that a *meteoroid is a solid body with a diameter greater than 0.1 m and less than $\approx$ 40 km, considering the lower and the upper limits of the objects influenced by the Yarkovsky and YORP effects.*

Advantages of this definition: it gives lower and upper limits that are independent of the observation.

Disadvantages: determining the asteroid size depends on the albedo and whatever it is measured in the visible or IR bands. In addition, many observations are necessary to determine it. Asteroids with a size near the upper limit could be difficult to classify.

3.3. *Completeness*

From the Small-Body Database Query (`https://ssd.jpl.nasa.gov/tools/sbdb_query.html#!#results`), we obtained a list of 31889 objects with a determined H from orbit classes Atira, Apollo, Aten, and Amor (data updated to February 3, 2023); and we made a completeness test. According to Figure 1 (lineal behavior), the sample is complete between $11 \leqslant H < 19$.

Based on this, another way of defining the term meteoroid would be: a *meteoroid is a solid object with magnitude H less than 11 and whose size is* $\geq$ 30 *microns.* In this sense, it would mean that meteoroids are objects whose sample is not complete and that are greater than micrometeorites.

Advantages of this definition: It gives well defined lower and an upper limits. In addition, we do not know many things about asteroids, but we do have the H of all of them (at least in the list that we used to make the completeness test).

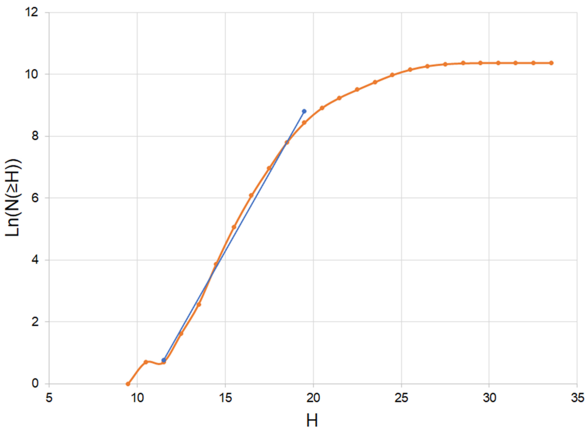

Fig. 1. Test of completeness. The intervals are such that $n \leq H < n+1$, n=9,10,11,...,32. The blue segment shows the range inside which the sample is complete. The color figure can be viewed online.

Disadvantages: The upper limit is going to move to $H > 19$ due to the efforts to complete the sample of all Near Earth Asteroids with $H < 22$ (e.g. Asteroid Day 100X Declaration).

3.4. *Society Risk*

3.4.1. *The Torino Scale*

The Torino scale was created by Binzel in 1995 and adopted in 1999 during a Conference of the International Astronomical Union in Torino, Italy. In 2004, Morrison et al. presented a new version of this scale and a very nice and clear exposition about several risk scales and the importance to communicate the public, in a simple and realistic way, the degree of hazard that an asteroid could present (Morrison et al. 2004). The Torino scale is a numerical scale, graduated in integer values between 0 and 10. Each value considers the impactor kinetic energy and the probability of impact. In the scientific community, it has been considered as an oversimplification of a multidimensional problem, but it is a proposal whose aim is to tell people if they must be concerned or not.

Number **0**, in the Torino scale means "No hazard", **1**, "Normal", numbers **2**,**3**, and **4**, "Meriting attention", numbers **5**, **6**, and **7**, "Threatening", and numbers **8**, **9**, and **10** mean "Certain collisions". In particular, number **2**, is defined as: "A somewhat close but not highly unusual pass near the Earth meriting attention by astronomers. An actual collision is very unlikely, with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to level 0". This number in the Torino scale is the greatest number that does not merit public attention (Morrison et al. 2004).

In this context, the proposal is to define meteoroid *as a solid object of size greater than 30 microns, whose Torino scale is* ≤ 2*; namely an object that is not a motive for public concern.*

Advantages of this definition: The physical meaning is simple: an object whose Torino scale is ≤ 2 means that we do not have to be worried about it, "it is only" a meteoroid.

Disadvantages: This does not provides much information about the physical parameters of the object, but the essence of Torino scale is to be a simple way to communicate to the public the importance of a collision with an object; so we must admit that this definition of meteoroid would not be useful to the scientific community.

3.4.2. *The Palermo Scale*

Another scale that assesses the risk of a collision is the Palermo scale. This one not only considers impact energy and probability of impact but also the time until an event occurs. Unlike the Torino scale, this one is not intended for communication with the public, but among astronomers (Chesley et al. 2002). Chesley and co-authors propose a value $\mathcal{P}$ that gives an idea about the impact risk compared to the background hazard that is the "threat from the entire asteroid and comet population averaged over very long time spans".

$\mathcal{P} > 0$ means that an asteroid at a given time is more threatening that the background hazard. $\mathcal{P} > -2$ implies an event greater than 0 on the Torino scale.

So, in this case, a meteoroid could be defined as *a solid object of size greater than 30 microns with* $\mathcal{P} < -2$.

Advantages of this definition: the lower and upper limits are well defined, and they indicate when an object is, or is not, a public concern.

Disadvantages: The upper limit will have uncertainties due to approximations to their diameters and masses. It is possible that e. g. asteroids can change their value of $\mathcal{P}$ due to better observations.

3.5. *Kinetic Energy and Size*

In the page of the Center for Near Earth Objects Studies there are data for 953 fireballs sensed by US Government sensors from April 15, 1988 to April 15 2023. These data include date/time (UT) of the peak brightness, latitude (deg), longitude (deg), altitude (km), velocity (km/s) and its components, total

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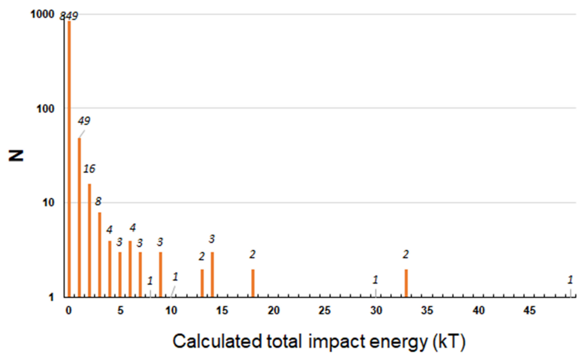

Fig. 2. Energy distribution function. Data from 952 fireballs sensed by the US Government. Figures placed above bars indicate the number of events with an energy, E, such that $n \leq E < n+1$, n=0,1,2...49. The color figure can be viewed online.

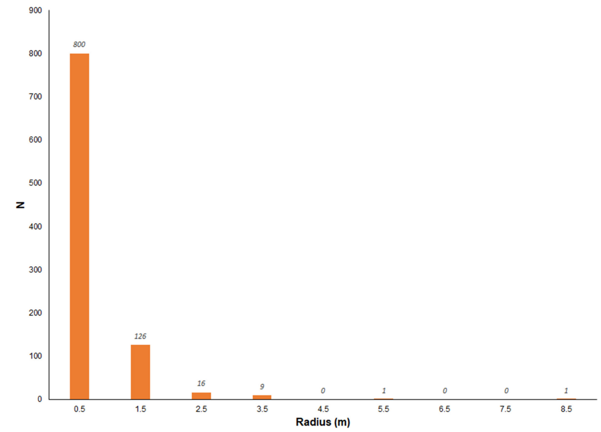

Fig. 3. Radius distribution function. Data from 953 fireballs sensed by the US Government. Figures placed above bars indicate the number of objects with a radius, r, such that $n \leq r < n+1$, n=0,1,2...,8. The last data with a radius of ≈ 9 m correspond to Chelyabinsk. The color figure can be viewed online.

radiated energy (J), and calculated total impact energy (kt) (https://cneos.jpl.nasa.gov/fireballs/). Velocity, when given, refers to the speed of the object before it impacts Earth's atmosphere. The total radiated energy is the integrated energy of the meteor brightness, which is an indicator of the pre-impact kinetic energy of the impactor (Brown et al. 2002). In the introduction of the consulted fireball database, it can be read that the calculated total impact energy is the kinetic energy of the impactor according to a relationship proposed by Brown et al. (2002):

$$\tau = (0.1212 \pm 0.0043) E_0^{0.115 \pm 0.075}, \tag{3}$$

where τ is the radiation efficiency, and E_0 is the observed radiation energy. Thus, the initial kinetic energy of the impactor, E, is

$$E = E_0/\tau = 8.2508 E_0^{0.885}. \tag{4}$$

Although Brown et al. (2002) discuss that equation (3) has several assumptions, like that bolids radiate as black bodies at 6,000 K which can be a poor approximation, Edwards et al. (2006) mention that this approximation is quite consistent with other estimations.

Figure 2 shows the energy distribution of these 952 fireballs (we excluded one with an energy of 440 kt that correspond to the Chelyabinsk event).

According to Korotev (2021), 95.1 % of the falls worldwide are stony meteorites, of which 93.1 % are chondrites, and 93.9 % of these are ordinary chondrites; so, in a first approximation, we can consider that the density of the typical material that falls into the Earth's atmosphere is similar to the mean density of the ordinary chondrites (H, L, LL), i.e. 3.54 g/cm^3 (Britt & Consolmagno 2004).

From previous data, and considering impactors as spheres, we converted the energy distribution function into a size distribution function using the kinetic energy equation and isolating the radius, r:

$$r = \sqrt[3]{\frac{3E}{2\pi\rho v^2}}, \tag{5}$$

where E is the calculated total impact energy, ρ is the mean density of the ordinary chondrites, and v is the velocity. We used the velocity given in the fireball database, whenever it datum exists (290 out of 953); otherwise, we used a mean velocity of 20.3 km/s (Brown et al. 2002). Thus, we obtained the distribution function given in Figure 3. 99.6 % of the elements of this sample (i.e. almost all of them) have a radius $\leqslant 3.5$ m, so we can define a meteoroid as an object whose diameter is less than 7 m.

Advantages of this definition: (a) It gives lower and upper limits that are independent of the observation instrument; and (b) under this definition, a meteoroid will be a typical object that entries the Earth's atmosphere and that does not represent a risk to people.

In a certain sense, the upper limit that we propose to define a meteoroid is similar to the lower limit proposed by Borovička (2016), because just as he considered the size of the particle as related to the maximum rate of influx of particles into our atmo-

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sphere, we are considering the largest size of common objects as the upper limit.

Disadvantages: The upper limit is obtained from two suppositions: a mean density and a mean velocity (in the most of the cases), so it is not very precise; however, we consider that it is a good approximation in round numbers.

4. COMMENTS AND DISCUSSION ABOUT SOME EVENTS

In this section we address some events and discuss them in the light of our definitions.

The Tunguska event occurred on the morning of June 30, 1908, when an object of an asteroidal or cometary nature (Robertson & Mathias 2019), with a radius of between 30 and 50 m (Hills & Goda 1993) or a diameter between 43 and 64 m (Jenniskens et al. 2019) exploded between 6 and 10.5 km above the Podkamennaya Tunguska river and damaged around 2,150 km^2 of Siberian taiga (Farinella et al. 2001). According to several studies, the energy released by the airburst could be between 3 and 50 Mt (Robertson & Mathias 2019; Jenniskens et al. 2019), although some authors mention that the most probable value could be between 10 and 15 Mt (Farinella et al. 2001; Jenniskens et al. 2019). This is the most intense event recorded historically, although there is geological evidence that an airburst and a series of ground impacts occurred near Abt Hureyra, Syria, approximately 12,800 years ago, and that this event may actually have been one of a series of impacts that could have affected an entire terrestrial hemisphere (Moore et al. 2020).

Geological and archaeological evidence indicate that another Tunguska-like event, perhaps even slightly more intense, destroyed the city of Tall el-Hammam, located northeast of the Dead Sea, approximately 3600 years ago (Bunch et al. 2021).

These three events could be classified as 8 or 9 on the Torino scale, but they would definitely not be considered meteoroids, according to the definition proposed in § 3.5.

The Chelyabinsk event, Russia, occurred on February 15, 2013. On this occasion, it is estimated that a rocky body 19.8 ± 4.6 m in diameter entered the Earth's atmosphere with a kinetic energy of 590 ± 50 kT. On this occasion, in the city of Chelyabinsk, some 1,210 people were injured, mainly due to the broken glass from the windows that were ejected (Popova et al. 2013). In this case, due to the energy of the object and its size, it is definitely an asteroid according to any of the proposed definitions, but once its approximate size or energy is known, it is evident that it is an asteroid also according to the definition proposed in § 3.5.

On February 12, 2023, the object 2023 CX1 was discovered, only several hours before it entered the Earth's atmosphere. According to the International Meteor Organization (IMO), this object, of around 1 m, is the 7th one to be discovered before colliding with our planet (https://www.imo.net/imminent-asteroid-entry-over-the-channel/). According to our definition in § 3.5, this object was a meteoroid, i.e. a common cosmic object that additionally was not a cause of concern for the public.

At around 3:50 p.m. on February 10, 2010, near the border between the Mexican states of Puebla and Hidalgo, a cosmic object entered causing great commotion among the population. Many people heard a loud crash, but we only found 12 people who saw it. Thanks to these witnesses we were able to determine that the direction of movement of the object was between west-east and 30° to the northeast (Cordero et al. 2011). Comparing the effects of this event (vibration of windows and the floor, the observation of a fireball and the noise) with the event of Curuça that was more intense (Cordero & Poveda 2011), it is very likely that the object had a size of a few meters at most. On February 22, 2011, a similar event occurred, this time between the states of Zacatecas and Aguascalientes. According to the definition in § 3.5, both events would correspond to a meteoroid. Here it is necessary to remark that some important events have occurred in February. These cases could be at the limit of the size or energy of our last definition, but they could be considered to be meteoroids because they did not represent a real risk for the people, and their energies were much less than Chelyabinsk's.

5. CONCLUSIONS

The objective of this work was to propose a definition for the term meteoroid. To do this, we analysed several criteria, some of them discussed by other authors: Yarkovsky and YORP effects, completeness of NEAs sample, society risk, kinetic energy and size.

As we mentioned before, with these criteria we only analysed the upper limit of the size of a meteoroid which coincided with the lower limit established by the IAU.

In each subsection we proposed a definition and gave advantages and disadvantages of each one.

Beech & Steel (1995), established the upper limit of a meteoroid at 10 m, because objects with sizes smaller than that were difficult to detect, i.e. a meteoroid was an object that telescopes could hardly observe. With this in mind, better telescopes would decrease the upper limit of a meteoroid. Rubin & Grossman (2010) do not clarify explicitly why they adopt 1 m as the upper limit of a meteoroid, but it looks like they considered that our telescopes are able to detect objects as small as this size. Whatever the reason, we consider that if we based the definition on our capacity to detect objects, the definition of a meteoroid would be nonsense in the future. Even now, we consider that the meteoroid definition is rather arbitrary and does not give information about the object.

As it was commented in previous sections, the definitions proposed here have advantages and disadvantages. But we consider that among them there is one that can be useful: *a meteoroid is a solid body that comes from the interplanetary medium and whose diameter is between 30 microns and 7 m.* In other words, meteoroids are objects greater than 30 microns whose entry into the Earth's atmosphere is very common and does not represent a risk to people. This definition is supported by 34 years of observations.

Previous definition do not make clear the nature of the body. It could be an asteroid, comet, planet or even a rocket, a satellite, or a part of them. In this sense, we propose that *a meteoroid is a natural solid body, that comes from interplanetary medium and whose diameter is between 30 microns and 7 m.* Rockets, artificial satellites or their remains could be named *artificial objects*, in general, no matter their sizes or materials. We are aware that to distinguish between natural and artificial bodies is not always possible, but the latter do not have the same size distribution function as the former, so they do not necessarily can be described in the same manner. Thus, they do not enter in the proposed definition.

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