Dynamic Sources of Contemporary Hazard from Meteoroids and Small Asteroids

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Abstract Ground-based observations of meteors and fireballs increase our data and statistics on meter-sized events entering the Earth's atmosphere. Impacts by larger bodies are less frequent and telescopic surveys to find potentially hazardous objects are still crucial to infer the flux of these over long timescales. Telescopic surveys provide significant data on Near Earth Asteroids of few tens or hundreds of meters in diameter that can be only detected when these bodies are close to the Earth. Statistically, bodies with a diameter from a few meters up-to about a 100 m can be considered as the most direct source of contemporary hazard. Of course, larger bodies will do more damage, but impact less frequently. The behaviour of stony bodies interacting with the atmosphere is reasonably well known, but little is known about the either the flux or the behaviour of materials from dormant comets that are often associated with meteoroid streams and small Near Earth Objects. We will introduce some examples that meter-sized meteoroids following high-inclination, and eccentric orbits are not necessarily fragile, and can trace the existence of hazardous objects: dormant comets or Damocloids being an example. From all the available data, a better understanding of the rate at which asteroids impact the Earth can be derived. If meteoroids of cometary origin are included the flux of objects into the Earth's atmosphere will be increased (Space Sci Rev 84(3/4): 327–471, 1998). However, the typical strengths of such meteoroids are too low to survive ablation in the upper atmosphere, so that they are unlikely to impact the ground. However, events such as that over Tunguska in 1908, where an air burst caused considerable damage over a large area, indicates that we should not underestimate fragile bodies as potentially hazardous sources. New missions aimed at returning samples of Near Earth Asteroids to Earth for analysis (Osiris-REx and Hayabusa 2) are very important because they will deliver to our laboratories materials probably

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non-sampled in meteorite collections. A better understanding of the composition of Near Earth Objects will allow the most efficient deflection techniques to be developed so that they present no hazard to human beings.

1 Introduction: NEO Fragments as a Source of Hazard to the Earth

For several decades now, there has been a concern over the threat posed to the Earth from impacts by Near Earth Objects, originating in both asteroids and comets and networks set up to detect them (see for example Gehrels et al. 1972; Chapman et al. 1982, 1989). In 1996 a Resolution of the Council of Europe was issued to promote the development of world-wide programs for the search and physical characterization of Near Earth Objects (NEOs). These bodies have orbits with perihelion distance $q < 1.3$ astronomical units (AU) and aphelion distance $Q > 0.983$ AU. As of December 24, 2015, there are about 13,600 objects known. Amongst these, many belong to well-known groups, 7292 are Apollos, 979 are Atens and 16 are Atiras (Table 1). Members of these groups are typically rocky bodies with diameters from ten meters up to few kilometers, and are usually called Near Earth Asteroids (NEAs). Near-Earth space is dominated by a population of thousands asteroids, compared with about 100 (104 at the current time) dark objects that have dynamical and physical properties suggesting that they are dormant or extinct comets (Jenniskens et al. 2007). The composition of these dark objects is still poorly known. If we need to deflect them, we must make every effort to determine their nature through studying their physical and reflective properties (Trigo-Rodríguez et al. 2014).

Despite the large number of recent discoveries, there is an urgent need to complete the current NEO population surveys so that all bodies larger than a few tens of meters have been discovered. This is not the case at present as is illustrated by two nearly simultaneous, but apparently unrelated events. On February 15, 2013 the scientific community correctly predicted the close approach, within 27,700 km, of the roughly 30-m near-Earth asteroid 367943 Duende (previous temporary designation 2012DA14), but failed to predict the far more dramatic direct collision of an 18-m in diameter asteroid just southwest of the Russian city of Chelyabinsk about 16 h earlier. More than a ton of meteorites reached the ground and were recovered. This meteorite, being named Chelyabinsk, exemplifies the shocked nature of materials reaching the near-Earth space (Fig. 1), and the damage caused by air burst (Wasson 2003; Boslough and Crawford 2008). As the program Protec-2-2014 from the Horizon 2020 is entitled "PROTECTION OF EUROPEAN ASSETS IN AND FROM SPACE-2014-LEIT SPACE" and has as specific goals to create knowledge about these bodies in view of their future exploration and mining potential, this event was of interest to this project.

The near-Earth population is diverse, but it is dominated by chondritic asteroids mostly formed out of silicates and metals. Such undifferentiated bodies are a source

Table 1 The definitions of the orbits of the various Near Earth Object groups and their respective acronyms (Adapted from NEO JPL)

Group	Description	Orbital definition
NECs	**N**ear-**E**arth **C**omets	$q < 1.3$ AU, $P < 200$ years
NEAs	**N**ear-**E**arth **A**steroids	$q < 1.3$ AU
Atiras	On similar orbits to asteroid 163693 Atira	$a < 1.0$ AU, Q <0.983 AU
	Orbits are contained entirely with the orbit of the Earth	
Atens	On similar orbits to asteroid 2062 Aten	$a < 1.0$ AU, Q >0.983 AU
	Earth-crossing NEAs with semi-major axes smaller than Earth's	
Apollos	On similar orbits to asteroid 1862 Apollo	$a > 1.0$ AU, q <1.017 AU
	Earth-crossing NEAs with semi-major axes larger than Earth's	
Amors	On similar orbits to asteroid 1221 Amor	:$a > 1.0$ AU, $1.017 < q < 1.3$ AU
	Orbits exterior to Earth's but interior to Mars'	
PHAs	**P**otentially **H**azardous **A**steroids: NEAs whose Minimum Orbit Intersection Distance (MOID) with the Earth is 0.05 AU or less and whose absolute magnitude (H) is 22.0 or brighter	$MOID <= 0.05$ AU, $H <= 22.0$

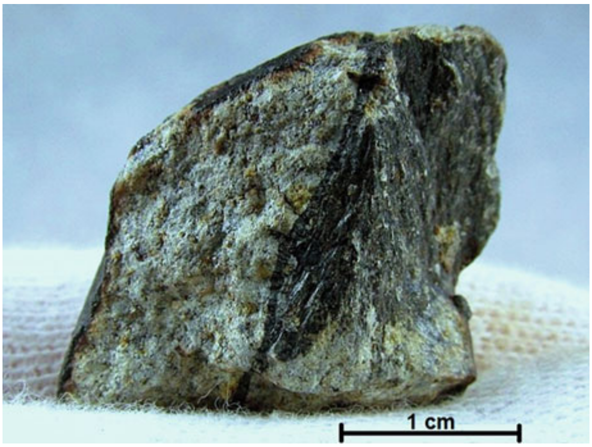

Fig. 1 A specimen of the Chelyabinsk meteorite that was recovered by an international expedition. This fragment can now be found in the IEEC-CSIC meteorite collection. The classical light lithology of ordinary chondrites is diversified by the presence of a dark lithology with significant amounts of shocked minerals, impact-generated veins and opaques (J.M.Trigo/CSIC-IEEC)

of precious elements that are rare in the Earth's crust and other planetary bodies (see Martínez-Jiménez et al., 2017). An influential book in this area was *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, written by John S. Lewis (1997). Before its publication, asteroid and comet mining was confined to the realm of science fiction. Today the required technology is available to make this a reality. In fact, such direct application of asteroidal materials as mineral resources is the key point for transforming risk assessment from an issue of public safety into an opportunity for technical and, industrial development. Seen in this way, justifying asteroid research and exploration in the near-Earth space is relatively simple. We should not forget that meteorite collections contain a quite biased sample set of diverse materials but the diversity of the sample can be increased by promoting the robotic exploration of these Near Earth Objects (see e.g. Trigo-Rodríguez and Blum 2009a, b).

Despite the difficulties of getting samples of most of these NEO's, sometimes *Mother Nature* gives us a helping hand. Large fireballs sometimes result in the fall of a meteorite that can be recovered, while often meteoritic material can be recovered without the fireball being witnessed. In either case, meteorites provide a direct source of materials from asteroids reaching the Earth vicinity, and are not seen as dangerous because not clear casualties are historically reported (Yau et al. 1994). This chapter will describe the challenging diversity of the nature of bodies moving in the near-Earth environment stresses the needed to bring together several different research lines in order to gain insight about their real nature and to inferring ways to minimize the hazard resulting from a direct Earth impact. We will also identify here the main sources of impact hazard to Earth, and the existence of quite unexpected populations of dangerous bodies following high-inclination orbits.

2 Meteorite Falls: Clues on the Origin of Hazardous Meteoroids

The most primitive materials arriving to Earth come from undifferentiated comets and asteroids (Nesvorny et al. 2003, 2006). If a stony meteoroid is to survive the passage through the Earth's atmosphere and produce a detectable meteorite on the ground, the initial body should exceed about half a meter. Such a meteoroid would generate a very bright *fireball* or even *superbolides* with brightness greater than magnitude-16. Such bright fireballs are very rare and can occur anywhere at any time. The reliability or otherwise of the observations is a matter of luck and will vary from event to event. Fireball networks around the world have observed thousands of orbits of fireballs during the last decades and determined their orbits, but in most cases the meteoroid did not survive passage through the atmosphere so that the recovery of a meteorite following a fireball is a very rare event. The first was the Pribram event on 7 April 1959 (For a review of this topic, see e.g. Trigo-Rodríguez et al. 2015). At the time of writing, 21 meteorites exist where the heliocentric orbit has been calculated from observations of the fireball generated by the passage of the meteoroid through the Earth's atmosphere (Table 2). About half of these meteorite recoveries were achieved because the luminous phase was imaged by a fireball network carrying out routine monitoring. The remainder came through casual and fortuitous observations. The reliability or otherwise of the observations is a matter of luck and will vary from event to event. Some are relatively good while others are less trustworthy, depending on the type, quality and number of records. Some events were imaged by accident by untrained observers. However, modern digital cameras have allowed casual images to be obtained even in day-time, producing valuable records of the luminous fireball phase that might be calibrated (see e.g. Trigo-Rodríguez et al. 2006). Even though the fireballs are extremely bright, the progenitor meteoroids are still less than a few meters across, and so are usually too small to be recognized by telescopic monitoring programs searching for potentially hazardous objects. However, there are some exceptions such as 2008 TC3, a small asteroid about 5-m across that disrupted over the Nubian desert and produced the Almahatta Sita meteorite (Jenniskens et al. 2009).

Collisions within the main asteroid belt (hereafter MB) have often been invoked as the cause for delivering small to moderate-sized asteroids to Earth (see e.g. Chapman et al. 1989; Davis et al. 2002). It is obvious that a collisional cascade of events produce smaller bodies that are subjected to non-gravitational forces. Among them, the Yarkovsky effect is a subtle force due to the asymmetric absorption and re-radiation of solar energy of the asteroid in space. It produces a progressive loss of energy and an inward migration of their orbits. Consequently, it was first realized that small asteroids and meter-sized meteoroids are crossing resonances mainly by the Yarkovsky effect, not by collisions (Farinella and Vokrouhlický 1999). Also the so-called YORP effect is a key force that changes the spins of small bodies, sometimes spinning them so fast that they break apart. These non-gravitational effects are also producing significant effects on the dynamic evolution of meter-sized and smaller meteoroids (Jenniskens 1998; Ceplecha et al. 1998). Morbidelli and Nesvorný (1999) demonstrated that numerous resonances are present in the MBA delivery of meteoroids and small asteroids to the near-Earth space. Another clear source of meteoroids reaching the Earth's atmosphere is of comets. The close relationship between comets and meteoroid streams was established in the latter part of the nineteenth century (see Williams 2011), well before the nature of comets was known. Comet ices sublimate as they approach the Sun and the gas outflow drags dust particles onto heliocentric orbits that are slightly different from that of the parent comet, forming coherent meteoroid streams (see Williams 2004a, b). Though the orbits are affected by planetary perturbations, they typically remain as coherent streams for tens of thousands of years. These are seen as meteors when the Earth passes through such a stream. Given sufficient time, streams loose their coherence due to a number of factors, close planetary encounters, Pointing—Robinson drag and collisions. These then form a part of the general interplanetary dust background and are seen as sporadic meteors when they meet the Earth's atmosphere (see Williams 1995) these sporadic particles move on orbits that are unrelated to the parent body orbit and so classifying them as cometary or asteroidal

Table 2 List of recovered meteorites with reliable orbital information by chronologic order

						Orbital elements			
Meteorite name	Year of fall	Type	Vg (km/s)	q (AU)	1/a (AU^{-1})	e	i (°)	ω (°)	Ω (°)
Příbram	1959	H5	17.43	0.78951	0.416	0.6711	10.482	241.75	17.79147
Lost City	1970	H5	14.2	0.967	0.602	0.417	12.0	161.0	283.0
Innisfree	1977	L5	14.2	0.986	0.534	0.4732	12.27	177.97	316.80
Peekskill	1992	H6	14.7	0.886	0.671	0.41	4.9	308	17.030
Tagish Lake	2000	C2-ung	15.8	0.884	0.505	0.55	2.0	224.4	297.9
Morávka	2000	H5	19.6	0.9823	0.541	0.47	32.2	203.5	46.258
Neuschwanstein	2000	EL6	20.95	0.7929	0.417	0.670	11.41	241.20	16.82664
Park Forest	2003	L5	16.1	0.811	0.395	0.680	3.2	237.5	6.1156
Villalbeto de la Peña	2004	L6	16.9	0.860	0.435	0.63	0.0	132.3	283.6712
Bunburra Rockhole	2007	Eucrite	13.4	0.6428	1.175	0.245	9.07	209.87	297.59528
Almahata Sitta	2008	Ureilite-an	12.42	0.8999	0.7644	0.31206	2.5422	234.448	194.10114
Buzzard Coulee	2008	H4	18.0	0.961	0.8130	0.22	25.5	212.0	238.9
Maribo	2009	CM2	28.5	0.481	0.45	0.8	0.26	99.0	117.64
Grimsby	2009	H5	20.9	0.9817	0.490	0.518	28.07	159.865	182.9561
Jesenice	2009	L6	13.78	0.9965	0.571	0.431	9.6	190.5	19.196
Mason Gully	2010	H5	14.53	0.98240	0.405	0.6023	0.832	18.95	203.2112
Košice	2010	H5	10.3	0.957	0.369	0.647	2.0	204.2	340.072
Sutter's Mill	2012	C	28.6	0.456	0.386	0.824	2.38	77.8	32.774
Novato	2012	L6	13.67	0.9880	0.478	0.526	5.51	347.35	24.9900
Chelyabinsk	2013	LL5	19.03	0.738	0.581	0.571	4.98	107.67	326.459
Annama	2014	H5	24.2	0.634	0.503	0.69	14.7	264.8	28.611

The uncertainty in each orbital element is not given here for simplicity, but it is implicit in the last figure given
For a full list of references see Trigo-Rodríguez et al. (2015)

in origin is harder (see Jopek and Williams 2013; Williams and Jopek 2014). The flux of low-strength aggregates associated with comets are preferentially disrupted in the upper atmosphere (Trigo-Rodríguez and Llorca 2006, 2007; Trigo-Rodríguez and Blum 2009a, b). Some arrive with the right geometry and velocity to survive as Interplanetary Dust Particles, but most are ablated and or disaggregated in the upper atmosphere as a consequence of their aerodynamic deceleration.

The Minimum Orbit Intersection Distance (MOID) can be used for evaluating the possibility of Earth encounters with an NEO. However, it does not indicate whether or not the two objects actually have an encounter at this minimum distance (Binzel et al. 2010). These objects usually have significant errors in their published orbital parameters and additionally non-gravitational effects usually make that the uncertainty in its location increases much more rapidly than the knowledge of the orbit itself. Thus, we are forced to continuous monitor these objects using ground-based telescopes, especially for large PHAs. Despite of these efforts, and mainly due to current surveys' observational limitations, we expect a very short notice for smaller asteroids or large meteoroids as was exemplified by Chelyabinsk or Almahata Sitta events (Brown et al. 2013; Jenniskens et al. 2009).

In summary, the different chondrite classes (Fig. 2) are basically conglomerates of fine dust (a mixture of silicates, oxides, metal, sulfides and organic constituents, see Fig. 3), chondrules, and refractory or mafic inclusions (Weisberg et al. 2006). Some of them, e.g. ordinary chondrite groups, were significantly metamorphosed in moderately large asteroid progenitors. The primordial water content in the different groups is difficult to assess, but aqueous alteration minerals have been identified even in ordinary chondrites. In general, chondrites containing Fe-metal are indicative of being anhydrous in origin. We also know that many carbonaceous chondrite groups are unprocessed because they exhibit unequilibrated minerals, and also contain interstellar grains with isotopic anomalies that survived processing in the solar nebula and accretionary processes when incorporated to these rocks (Huss et al. 2006; Trigo-Rodríguez and Blum 2009b). Aqueous alteration plays against pristinity as there is clear evidence that some isotopic ratios (like e.g. D/H) are altered during parent body aqueous alteration processes (Alexander et al. 2012; Marty 2012).

Achondritic meteorites are not so common, but provide significant information about the composition and evolution of planetary bodies. From the inferred orbits of achondrites we could expect a significant breakthrough in our understanding of the main dynamic pathways for their delivery to the near-Earth space. In any case, Table 2 clearly shows that we are still far from such a goal as we only know the orbit of an eucrite called Bunburra Rockhole (Bland et al. 2009), and an anomalous ureilite called Almahata Sitta (Jenniskens et al. 2009). We have also recently identified that a small Apollo asteroid designed as 2012XJ112 is the source of bright bolides whose emission spectra seem to be clearly achondritic (Madiedo et al. 2014a).

Achondritic asteroids are also common in the MB. A good example is asteroid 2867 Steins that was studied by Rosetta (ESA) mission during a fly-bye approach. On the basis of these observations, Barucci et al. (2005) classified Steins as an

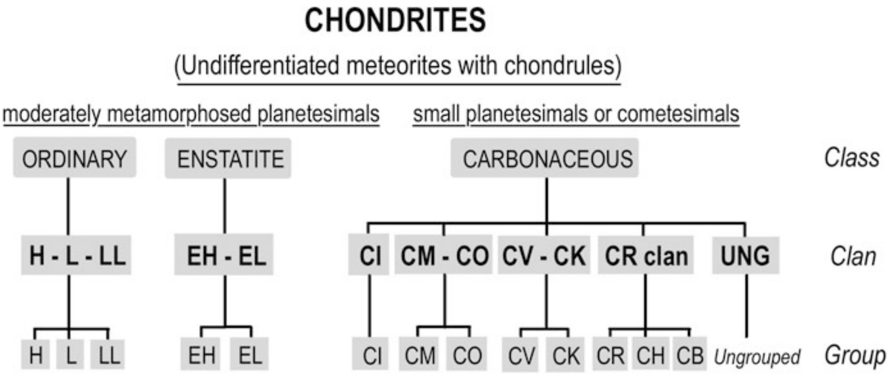

Fig. 2 Main classes, clans and groups of chondritic meteorites. A tentative origin is suggested, but not with idea of being exhaustive (Adapted from Trigo-Rodríguez 2015)

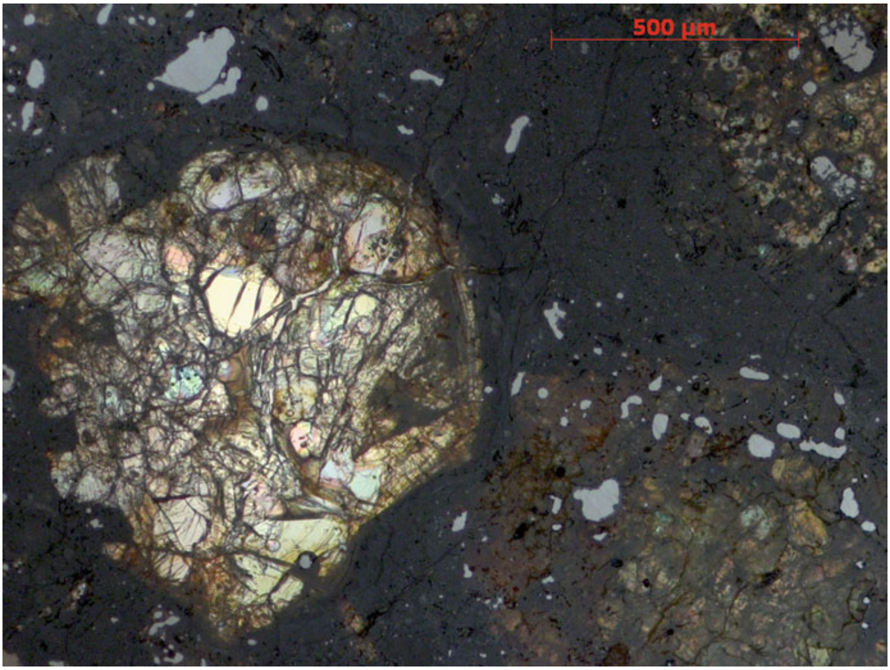

Fig. 3 A thin section of the GRA 95229 CR chondrite from NASA Antarctic collection seen in reflected light with a Zeiss petrographic microscope. Several mm-sized porphyritic olivine-rich chondrules are dominant in the image. Fe-Ni metal grains in grey colour are distributed in the chondrules or isolated in the fine-grained dark matrix (J.M.Trigo/IEEC-CSIC)

E-type asteroid based on visual and near-infrared spectra. E-type asteroids may be similar to enstatite achondrite meteorites (aubrites) and display only grey to moderately red colors. 2867 Steins reflectance spectrum exhibits an unusually strong 0.50 μm feature and a significantly redder spectral slope than previously studied E-types, or their terrestrial meteorite analogs (Weissman et al. 2008).

3 Space Missions Relevant to the Study of Asteroids

Several space missions are currently either ongoing or envisaged for the next decades that are particularly relevant to the study of asteroids. There is a real need to understand the nature of many of the asteroids in the MB, particularly those that feed the near-Earth region through planetary resonances. Because of the intrinsic difficulty in comparing asteroid and meteorite spectra, we need to increase telescopic observations and discovery surveys in order to increase our knowledge on these bodies. We also require sample-return dedicated missions.

The main goal of ESA's Rosetta mission was to rendezvous with periodic comet *67P/Churyumov-Gerasimenko* (67P/C-G) and spend approximately 2 years studying that comet. In addition the Philae landed on the surface providing some date on the internal structure and near-surface environment En route to the comet, Rosetta flew by two MB asteroids, *2867 Steins*, on September 5, 2008, and *21 Lutetia* on July 10, 2010, and carried out observations of them.

A particular mission that should lead to a significant progress in our global knowledge about asteroids is *Gaia*. It was launched on 19 December 2013, and, after an extended commissioning phase started scientific operations in September 2015. *Gaia* performs very accurate astrometry, but also obtains spectral data of the sources through a continuous scanning of the sky. Moreover, the fully automated selection of the sources also ensure that nearly all Solar System objects brighter than +20 visual magnitude will be observed by this unique space observatory (Tanga and Mignard 2012). Gaia has two telescopes with a rectangular aperture of $1.45 \times 0.5\ m^2$ observing simultaneously two fields separated by an angle of 106.5°. Both telescopes have a common focal plane composed of 106 CCD detectors: 77 of them will perform the astrometry and the photometry of the sources, while 14 CCDs will measure the light dispersed by two prisms, in order to obtain the color of all sources observed by the astrometric focal plane. Finally, another 12 CCDs will collect the data coming from the high resolution spectrometer (RVS) to measure the radial velocity of the sources, while the remaining CCDs are used for calibration purposes. During its 5 year life, it is expected to observe about 400,000 asteroids on average 60 times, discovering many new asteroids in the process. From the reflectance spectra planned, it should also produce a breakthrough in our understanding of the different minor bodies populations.

A good example of the importance of sample-return initiatives to understand the nature and evolution of asteroids come from the Japanese Space Agency (JAXA) Hayabusa mission (Fujiwara et al. 2006). Asteroid Itokawa (Fig. 4) is our best

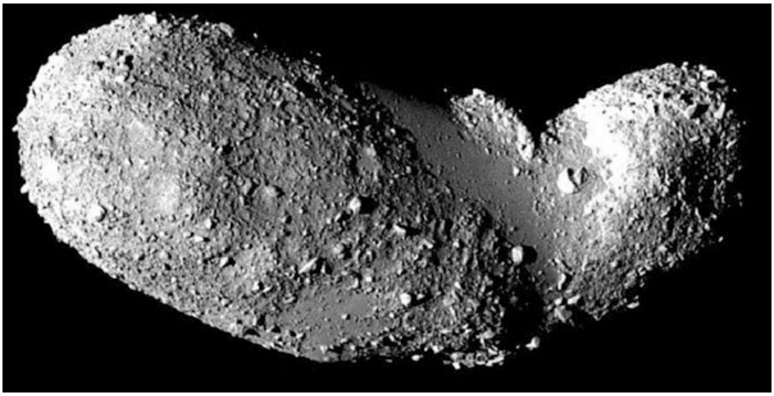

Fig. 4 Image of asteroid 25143 Itokawa our best known example of rubble pile (Hayabusa/JAXA)

studied rubble pile example, necessarily created from a complex collisional and re-aggregation history that exemplifies how evolved are the bodies dominating the near-Earth environment (see e.g. Chapman et al. 1989). The smallest asteroids typically delivered by mean motion planetary resonances have suffered catastrophic disruptions, and collisional cascade processes as envisioned by Michel et al. (2001, 2002). In fact, catastrophic disruptions are behind the formation of asteroidal cluster or families (Nesvorný et al. 2002). Then, it is not so surprising after all that shock effects in different degree are quite commonly reported in meteorites delivered to Earth.

There are two currently ongoing sample-return missions with significant cosmochemical interest addressing pristine asteroids associated with carbonaceous chondrites. The *Hayabusa 2* mission is a Japanese Space Agency (JAXA) initiative focused on returning samples from Apollo asteroid *162173 Ryugu* (also known by the provisional designation *1999* JU_3). This body belongs to a rare Cg spectral type that is defining a C-type asteroid presumably formed by carbonaceous chondrites, but exhibiting hydrated features in its reflectance spectrum like those observed in G-type asteroids represented by *1 Ceres*. The return of samples to Earth is expected to occur in December 2020 (Nakamura et al. 2015).

The *OSIRIS-Rex* NASA mission is focused in returning samples of asteroid (*101955*) *Bennu*. This body likely originated as a discrete asteroid in the inner MB approximately 0.7–2 Gyr ago as a fragment from the catastrophic disruption of a pristine carbonaceous asteroid (Lauretta et al. 2015).

Both sample-return missions will make history in returning primitive materials for study in terrestrial laboratories. Another proposed relevant mission is the *NASA Asteroid Redirect Mission* (*ARM*). This will be the first-ever robotic mission to visit a large near-Earth asteroid, collect a multi-ton boulder from its surface, and use it in an enhanced gravity tractor asteroid deflection demonstration. The spacecraft will then redirect the multi-ton boulder into a stable orbit around the moon, where astronauts will explore it and return with samples in the mid-2020s (Mazanek et al. 2013).

Unfortunately, a European sample-return mission called Marco Polo-R, initially pre-selected by the European Space Agency (ESA), failed final selection but promoted a significant scientific European cooperation in this field (Barucci et al. 2012). Undoubtedly such initiatives promote scientific cooperation in the context of the planned Asteroid Impact Deflection Asteroid mission (AIDA).

4 Hazardous Meteoroids Originating from Near Earth Asteroids

The possibility that meteorite-dropping bolide complexes associated with near-Earth asteroids could exist was first proposed by Halliday (1987). Trigo-Rodríguez et al. (2007) also found dynamic associations between large meteoroids and Near Earth Objects (NEOs). Many asteroids are rubble piles and so probably do not require a collision in order to be disrupted (Trigo-Rodríguez et al. 2009a, b; Madiedo et al. 2014a, b, c). The fragmentation process is likely to produce many meter-sized rocks as well as larger boulders and rubble pile asteroids that could form a complex of asteroidal fragments once disrupted all initially moving on nearly identical orbits. Detecting such families or associations may not be easy because the temporal stability of such orbital complexes is quite short (few tens of thousands of years) as consequence of planetary perturbations (Pauls and Gladman 2005), except perhaps for those cases exhibiting orbits with high inclination, where life-times can be considerably higher (Jones and Williams 2008). Disruptive and collisional processes also cause a divergence in the orbits (Bottke et al. 2002). Significant brecciation, and shock-induced darkening has been found e.g. in the Almahata Sitta and the Chelyabinsk meteorites (Kohout et al. 2014; Bischoff et al. 2010) indicating that collisions played a role in their evolution.

Pravec et al. (2012) studied a sample of 583 MB asteroids and NEAs and found that the typical albedo for carbonaceous asteroids (Tholen/Bus/DeMeo spectral classification: C/G/B/F/P/D) is 6 %, while the associated with ordinary chondrites (spectral classes S/A/L) is about a 20 %. It is not so surprising then that the NEA population discovered so far is dominated by the latter ones.

Other mechanisms for delivering meter-size meteoroids to Earth include tidal fracturing caused by close encounters with planets and fast rotation (Trigo-Rodríguez et al. 2007, 2008; Chapman 2010). Meteoroids ejected by a fast rotator could have quite low de-coherence timescales if we consider the YORP effect. Alternatively, a catastrophic disruption produce fragments in which typically the escape velocity is considerably smaller than the orbital velocity, so a large amount of the mass is ejected away at escape velocity (Bottke et al. 2005) which is considerably smaller than the orbital velocity. Consequently, a significant number

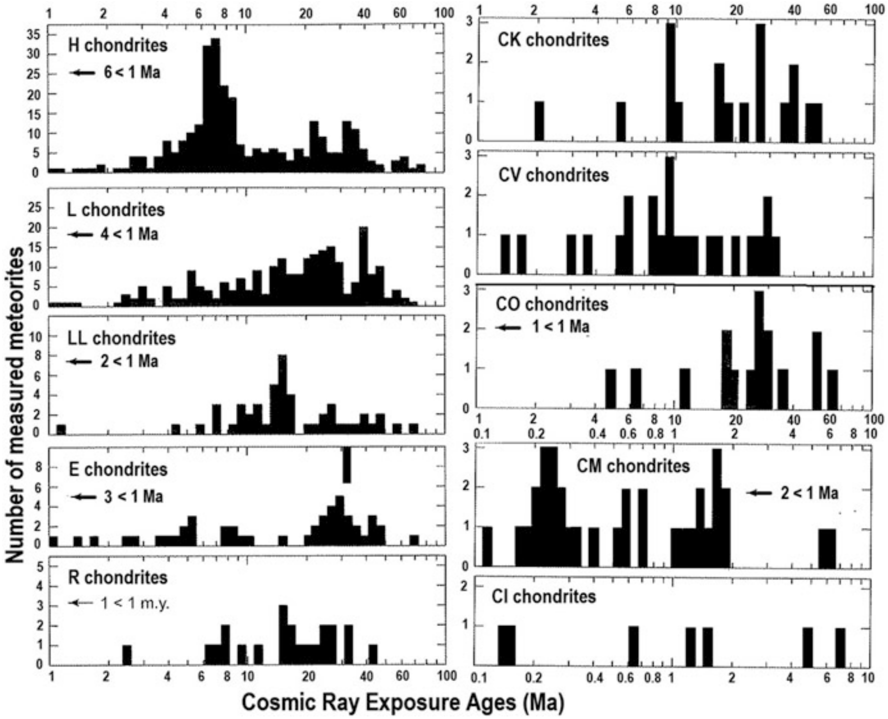

Fig. 5 Typical CREAs for chondritic meteorites (Adapted from Eugster et al. 2006)

of meter-sized pebbles or even boulders are released forming a stream of asteroidal fragments moving on nearly identical orbits (Williams 2004a, b; Jenniskens 2006; Trigo-Rodríguez et al. 2007). This is a likely source of meteorites to Earth, and it is more probable that such delivery from NEOs is dominated by low compressive strength materials: well fractured ordinary chondrites or well fragile carbonaceous chondrites (Trigo-Rodríguez and Blum 2009a, b).

While we cannot recover a more significant number of meteorites that have orbital information, some clues can be obtained from the study of Cosmic Ray Exposure Ages (CREAs) in meteorites inferred from the solar wind noble gases implanted in them during the movement around the Sun of the meter-sized progenitor meteoroids. It is generally accepted that the inferred CREAs corroborate that most meteorites reach the Earth after timescales of tens of Ma (see e.g. the review by Marti and Graf 1992). Such periods of time are consistent with meteorites delivered from the MB through dynamic resonances. A more exhaustive and recent review by Eugster et al. (2006) identified some chondrites exhibiting smaller CREAs (see Fig. 5).

If this hypothesis concerning the existence of a small, but significant fraction of meteorites being delivered from NEAs is correct, it is likely that a significant fraction of small meteorites found in Antarctica (where the minimum meteorite mass recovered is about one order of magnitude smaller than in the rest of locations) exhibit CREAs of few million years or even lower (Trigo-Rodríguez 2015). This is the expected timescale in which NEOs are crossing the near-Earth space before returning to the MB, and if they contribute significantly we should see at least some meteorites having such CREAs or even lower. First, some meteorites belonging to the L and H groups of ordinary chondrites exhibit CREAs lower than 1 Ma. Some examples are some finds: the H4 chondrite Cullison (CREA = 1.4 ± 0.3 Ma), the H5 chondrite Grove Mountains 98,004 (0.05 Ma), or the L6 chondrite Ladder Creek (CREA = 0.9 ± 0.1 Ma). For further details on these CREAs and references for the data outlined here see Eugster et al. (2007) compilation.

Many grouped and ungrouped carbonaceous chondrites remain to be studied and may contain fascinating clues on disruptive processes in their parent bodies like for example Elephant Moraine (EET) 96026, which that has an extremely low CRE age of 0.21 ± 0.03 Ma (Ma et al. 2002). Such CREAs can be perfectly consistent with a quick delivery from disrupted bodies (C-rich asteroids and extinct comets) located in the near-Earth space. It is important to mention that the typical CREAs inferred for ordinary chondrites is higher than for carbonaceous ones (see e.g. Fig. 5). In order to confirm these ideas to complete CREA data of small Antarctic chondrites seems essential, particularly these of carbonaceous nature.

5 Cometary Sources of Impact Hazard

Centaurs comprise a transitional population deriving from cometary reservoirs beyond Neptune that are crossing the orbits of giant planets (Jewitt 2008). Due to gravitational perturbations and the decay associated with their envisioned fragility, some of them could reach Earth-crossing orbits like it was found for comet 95P/Chiron (Hahn and Bailey 1990; Asher and Steel 1993). Recent claims have proposed a more careful study of the dynamic evolution and physical decay of these large objects (Napier et al. 2015).

This scenario invoking the importance of cometary bodies in impact hazard is not new. It is currently accepted that trans-Neptunian objects (TNOs) and centaurs, in chaotic orbits, evolve towards the inner planetary region (Duncan et al. 1995; Levison and Duncan 1997) at a significant rate via the Jupiter Family Comets (JFCs). These comets can be considered fragments of TNOs (Jewitt 2008) and participating as a significant source of impact hazard. Dynamic studies have found that comets forming part of such population become Earth crossers (Ipatov et al. 2007). They follow highly-eccentric orbits that can bring them to Earth vicinity at much higher relative velocities than typical asteroidal orbits, and usually are km-sized bodies. Although Earth encounters with JFCs are estimated to be one order of magnitude less frequent that with asteroids, the energy released can be several orders of magnitude because of their larger masses and much higher velocity. In a similar way that the collisional processing of asteroids produces most of the small asteroids crossing the near-Earth space, the origin of JFCs was explained by the progressive decay and subsequent inward orbital movement of TNOs (Emel'yanenko et al. 2004; Jewitt 2008).

By using visual observations reported 150 years ago in the Comptes Rendus de l'Académie des Sciences de Paris the atmospheric trajectory of the Orgueil CI chondrite has been reconstructed. Despite the intrinsic uncertainty of visual observations and estimating the duration of the luminous phase of that bolide, it was found that this rare meteorite could have been delivered from a JFC (Gounelle et al. 2006). There is growing evidence suggesting that meteoroids following high-inclination orbits are not necessarily fragile and might exist (Jones and Williams 2008). A meteorite fall occurred on July 6, 2007 over Cali, Colombia and visual observations of the bolide were compiled. The recovered meteorite was characterized as a rare H/L chondrite interloper that was identified as coming from the MB (Trigo-Rodríguez et al. 2009a, b). A potential meteorite dropping bolide called SPMN110708 "Bejar" appeared on July 11, 2008 with a pre-atmospheric orbit that indicated a plausible association with the debris of disrupted comet C/1919 Q2 Metcalf. The meteoroid was about one meter in diameter, it indicated that a cometary disruption can be source of meteorites (Trigo-Rodríguez et al. 2009; Williams 2011). Events in successive years close to the same time suggested that they should be investigated further, and other orbital solutions for the Cali event were explored. It is well known that visual observations introduce significant observational uncertainties and whether a unique solution can be obtained probably depends on the data set considered. We realized that another solution coming from the most extremely long trajectory observations was consistent with a grazing bolide with a radiant consistent with that estimated for Bejar. Is it possible that a high-inclination stream of meter-sized meteoroids originating from the disruption of comet C/1919 Q2 Metcalf exists?

The answer to the above question is probably positive. H/L ordinary chondrite falls other than Cali, occurred on similar dates but separated by several decades each (see Table 3). This cannot be casual given the small amount of H/L chondrites falls (4 so far) compared with the number of falls associated with H (366), L (417) or LL (99) group chondrites, usually coming from the MB (Meteoritical Bulletin Database 2016). The fall of these chondrite groups of chondrites **are** scattered all over the year (Grady 2000), while the H/L chondrites are concentrated between May and July (Table 3). To have the 4 H/L chondrites falls occurred in about a 3 months period corresponds to a probability of about a 6 % ($1/(4 \times 4)$, for each trimester chance). We should also remember that there are 4 H/L chondrite falls, compared with 882 chondrites belonging to another groups so the statistic is limited.

This evidence is interesting because it suggests that an important flux of meter-sized rocks currently reaching the Earth could come from high-inclination orbits that we are not taking into account, particularly in view that only a small amount of meteorites that fall on Earth are recovered.

The existence of meteorite streams was first suggested by Halliday et al. (1990) based on a number of fireballs in the Meteorite Observation and Recovery Program (MORP) and Prairie network databases with exceedingly similar orbits. The detailed data for 259 fireballs observed with MORP can be found in Halliday et al. (1996). Wolf and Lipschutz (1995) and Lipschutz et al. (1997), have argued that there is evidence from meteorite falls for the existence of meteorite streams.

Table 3 Compilation of H/L meteorite falls

Meteorite	Fall date (UTC)	Group & petrological subtype	TKM (kg)
Bremervörde	May 13, 1855	H/L3.9	7.25
Tieschitz	Jul 15, 1878	H/L3.6	28
Cali	July 6, 2007 21h32min	H/L4	0.478
Famenin	June 27, 2015 4h30min	H/L3.8–3.9	0.630

References: [1] Meteoritical Bulletin Database: http://www.lpi.usra.edu/meteor/index.php

We previously mentioned the recently found evidence of meteorite-dropping bolides associated with NEOs. A dynamic association between the orbit of NEO 2002NY40 and several bolides recorded over Spain and Finland was found (Trigo-Rodríguez et al. 2007). Babadzhanov et al. (2008) also found meteor showers dynamically associated with 2003EH1. Two meteorite-dropping bolides recorded over Spain were also clearly linked with PHA 2007LQ19 (Madiedo et al. 2014b). In addition, we also found a plausible dynamic link between the H5 chondrite Annama and PHA 2014UR116 (Trigo-Rodríguez et al. 2015). Also recently a dynamic link has been also claimed between comet 2P/Encke, the Taurid complex NEOs and the Maribo and Sutter's Mill meteorites, though the spectra of the bodies obtained was inconclusive (Tubiana et al. 2015).

The relative absence of NECs compared with other groups of NEOs known so far seems to indicate that our surveys could miss a significant number of extinct or inactive comets. The recent discovery of 2015 TB145, with only 3 weeks of margin to take action in case of a direct encounter, is a fact that should not leave us indifferent. A major concern in our strategy should arise from the evidence of low-albedo comets with such a type of high-eccentricity orbits. The danger associated with this kind of objects is well exemplified with the encounter velocity of 35 km/s during the closest approach of 2015 TB145 is slightly farther away than the Earth-Moon distance. The low-reflectivity also made that the original 400 m in diameter estimate was lately reassessed into 600 m, once studied the radar images obtained from Arecibo and Goldstone. There is no doubt that the future study of this primitive object will take a scientific interest.

Another superbolide recorded from Spain on July 13, 2012 provided evidence that meter-sized bodies with high tensile strength can be associated with rare and hazardous Damocloids (Madiedo et al. 2013a). These bodies are named after asteroid 5335 Damocles and exhibit Halley-family or long-period highly eccentric orbits, but without showing a cometary coma or tail. It is evidence that some comets are formed by high-strength materials, also being a significant source of hazard lying in high inclination orbits that might escape to most asteroid surveys.

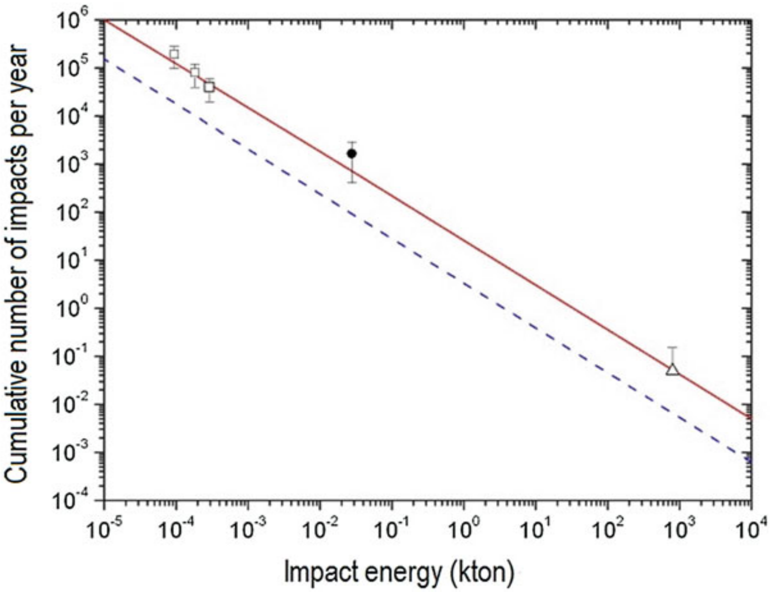

Fig. 6 Cumulative number of impacts per year as a function of the impact energy of the projectile. For details about the symbols please see the text (Adapted from Madiedo et al. 2014c)

Recent studies of lunar flares produced by sporadic meteoroid impacts have also confirmed that the flux of large meteoroids is higher than previously suspected (Ortiz et al. 2006). The cumulative frequency of impacts with the Earth as a function of the energy of the impact is shown in Fig. 6. The dashed line corresponds to the rate of impacts obtained by Brown et al. (2002), while the squares represent the results obtained by Ortiz et al. (2006) based on the analysis of flashes of impacts on the Moon. The continuous line corresponds to the frequency obtained from Ortiz et al. (2006). The result corresponds to the great impact on the Moon detected by Madiedo et al. (2014c). It is represented by the black circle, while the triangle corresponds to the impacts flow calculated by Brown et al. (2013) based on an analysis of the event of Chelyabinsk. There is no doubt that the evidence provided by infrasound and satellite flash detection of meter-sized projectiles is clearly relevant to flux estimates and it is outlined in (Tapia and Trigo-Rodríguez 2017)

6 Discussion and Conclusions

Fireball network evidence together with the information from recovered meteorites support the existence of a large diversity in the bodies contributing to Earth's contemporary impact hazard. Probably the relative absence of destructive events in the literature, but perhaps Tunguska and Chelyabinsk, is due to our relatively short written history. In the last century, some events have been clearly identified with asteroid or comet impacts, and significant progress is being made in our knowledge when meteorites are recovered from such rare events. This is a good reason to promote international cooperation in this regard, and try to decipher all routes of meteorites reaching our planet.

Consequently, the main conclusions of this review are:

1. Telescopic surveys are increasing the number of NEOs over the size range of tens to hundreds of meters, and the study of their physical and dynamic properties requires an interdisciplinary approach involving international cooperation. It opens the way of finding evidence of disruptions in the near-Earth environment, producing streams that can be source of meteorites over short-time scales.
2. The population of bodies crossing the Earth's orbit is extremely diverse. It is probably dominated by chondritic asteroids, but the presence of carbonaceous bodies is probably largely underestimated, particularly for small NEOs. This is because carbonaceous bodies have much lower albedos and following eccentric orbit escape to our ground-based biased monitoring techniques.
3. The collisional and dynamic pathways followed by NEOs until reaching our planet are biasing their populations towards high-strength materials that are the final products of successive collisions.
4. From the previous point, it is obvious that meteorite collections are not fully representative of the materials available in the Near Earth environment. There is a clear bias concerning low-strength materials that rarely survive to atmospheric entry or produce a crater, but likely produce air bursts and tektites.
5. Future sample return missions like OSIRIS Rex and Hayabusa 2 will develop new technology, and promote the study of asteroid samples in clean laboratories. Collecting new, previously non-sampled, materials from NEOs we will increase our capacity to develop palliative efforts, like e.g. much more efficient ways of deflecting asteroids.
6. Cometary samples are probably among the most fragile materials available in the solar system. Future cryogenic missions returning cometary samples could promote amazing discoveries on the first materials forming the protoplanetary disk.
7. Meter-sized meteoroids producing superbolides and following high-inclination, and eccentric orbits are not necessarily fragile, and can trace the existence of hazardous objects: dormant comets or Damocloids being an example.
8. H/L chondrites could have originated from disrupted comet C/1919 Q2 Metcalf. This was probably a rubble pile consisting of pieces of different petrologic nature from different parents, and a good example of the complex structure of a transitional body.

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