ESA'S ACTIVITIES ON THE BOUNDARIES BETWEEN NEO AND DEBRIS DETECTION

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ABSTRACT

As of 2018, over 210 spacecraft have been launched into interplanetary trajectories or towards Lagrange points in the Solar System. More often than not, these spacecraft on exploration missions were trailed by one or two stages from the launch vehicle that put them into orbit. The probability that these hundreds of objects would find themselves in the Earth–Moon system again is small but not negligible.

In relation to the observational activities over those types of objects, a number of scenarios have been recently exploited at ESA that speak of the synergies between the NEO observational activities and the SST ones. Such activities have been carried out in conjunction between the NEO Coordination Centre (NEOCC) at ESRIN and the Space Debris Office (SDO) at ESOC.

In this paper we present the activities performed by both teams firstly in the observational campaign in 2015 targeting the artificial object WT1190F. This object was discovered by an asteroid survey to be in a very high Earth orbit and in an impacting trajectory with Earth a few weeks later. A few months later, the launch of ExoMars provided a second opportunity for a further test of the interaction between NEO and SST observers. In this case we also contacted various observatories in the Southern hemisphere to support the follow-up of the object. Over the following years we obtained images of additional artificial objects that provided good test cases for NEO observational capabilities, including the OSIRIS-REx spacecraft during its 2017 Earth fly-by and the Tesla Roadster recently launched into an interplanetary trajectory.

To discern an artificial space debris object from a regular near-Earth object requires careful analysis of derived information such as area-to-mass ratio or colour-band photometry. In this work, we provide a review of such methods and characterise the trajectories of artificial space debris object which could interfere once more with the Earth–Moon system, including their observability. We also explain a novel metric to discern between the two types of objects after re-entry, based on observations of WT1190F. The expected differences and commonalities are analysed.

1 ESA'S NEO COORDINATION CENTRE

ESA's NEO Coordination Centre (NEOCC) is the office charged with the operation of a system to provide follow-up observations of NEOs, compute their orbits and provide other relevant information. NEOCC is located at ESA's site in Italy, ESRIN. This system is reachable via a 'technical web portal' at http://neo.ssa.esa.int. This portal went online in 2012 by federating several important European NEO services: the 'priority list' giving information on NEOs which are in need of observations, the NEO Dynamic Site (NEODyS) orbit determination and prediction system, the 'risk list' provided by NEODyS system showing all objects with a computed non-zero impact risk over the next 100 years and a physical properties database. In the meantime, some of these services have been migrated or are still under migration to the NEOCC.

Several functions are executed at the NEOCC:

- Follow up of asteroids in need of more observations to improve the knowledge of their orbits for their propagation in the future. For this, the ESA Optical Ground Station (OGS) is used on a monthly basis, as well as some supporting telescopes like ESO's Very Large Telescope (VLT), the Large Binocular Telescope (LBT) and OASI's telescope in Brazil

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(from Observatório Nacional Sertao de Itaparica), to mention just a few of them,
- The Orbit Determination System, which takes astrometric positional data of asteroids from the Minor Planet Center and computes high-precision orbits from these data. The orbit determination part of NEODyS was recently migrated to the NEOCC for these purposes. Orbits are later propagated 100 years into the future and the impact risk of these objects is computed. In this respect, the impact monitoring part from NEODyS is currently being migrated,
- The 'priority list', including a list of NEOs in need of observations. This list was developed by INAF/Rome. The complete code was migrated to ESRIN and is executed and maintained within the Centre,
- Inclusion of a physical properties database based on the EARN (European Asteroid Research Node) service, which is maintained by G. Hahn from DLR Berlin. A user interface was set up for future systematic updates of physical properties of NEOs. at the NEOCC.

The maintenance of the software services and the needed hardware is supported by ESA Space Safety's Data Systems (DS) team and Information and Communication Technologies (ICT) team. In addition an industrial team provides maintenance and evolution to the whole software system.

In summary, the following services are provided by NEOCC through its web portal:

- Risk list, with all NEOs having a non-zero impact risk in the next 100 years,
- Priority list, with the objects in need of observations in the short term,
- Close approaches list, with a table of all known objects approaching the Earth in the next year and another table with the close approaches of the past month,
- Close approach fact sheets for special close approach cases,
- Search functions to find information on NEOs, other asteroids and comets,
- News and newsletter archive,
- Discovery statistics,
- Orbit visualisation tool,
- NEO Chronology, as provided and maintained by Karel van der Hucht,
- An image database which is linked to the Solar System Object Image Search (SSOIS) system [1],
- Access to two stand-alone tools that can be downloaded and executed by external users: one prepared to produce NEO population and observability data (NEOPOP) and another one designed for NEO trajectory propagation (NEOPROP).

2 ESA'S SPACE DEBRIS OFFICE

Since the mid-1980s, ESA has been active in all research, technology and operational aspects related to space debris. The Agency's expertise is mainly concentrated at the Space Debris Office (SDO) located the European Space Operations Centre (ESOC), Darmstadt, Germany. The team at ESOC has developed long-standing experience in the areas of:

- Radar and optical measurements and their simulation;
- Development of space debris and meteoroid environment and risk assessment models;
- Analysis of debris mitigation measures and their effectiveness for long-term environmental stability;
- In-orbit collision risk assessments;
- Re-entry safety analyses;

SDO coordinates ESA's research activities on space debris such as measurements, modelling, protection and mitigation; coordinates such activities with national research efforts and provides operational services. Such services include operational collision avoidance for ESA and third party missions [2], re-entry predictions for artificial objects (https://reentry.esoc.esa.int), support to industry and academia on the properties of objects in orbit (https://discosweb.esoc.esa.int/), and software developments to help mission designers and operators to track the impact of space debris on their missions (https://sdup.esoc.esa.int).

ESA's SDO has also been a forerunner in the definition of European space surveillance activities, which ESA is now exploring under its Space Safety Programme (SSP, previously known as the Space Situational Awareness programme or SSA). This programme is now in its third period (2017-2019) and the Space Debris Office is providing a management function for the Space Surveillance and Tracking (SST) segment.

In SST, the development of the technologies for detection, cataloguing and follow-up of space objects, and of the derived applications for conjunction event prediction, re-entry predictions, and fragmentation event detection, is considered a first important step toward a European SST capability. ESA is focusing on research and development, supporting national initiatives, and ensuring complementarity with other European approaches to SST. From on-going national SST activities in Europe, a demand for larger cross-national SST components and technology development is expected to ensure the interoperability of developed systems. Examples of related planned ESA activities are space-based SST sensors, sensor and data centre processing software facilitating data exchange mechanisms and common data-processing techniques and formats.

Through the SSP, ESA's expertise will be exploited in supporting the research, development and coordination of space-related technologies in a multinational environment, and in assessing and further developing the relevant emerging technologies in close coordination with the appropriate technology domains.

3 SPACE DEBRIS IN HELIOCENTRIC ORBITS

The amount of artificial objects in interplanetary space is currently small compared to natural objects: as of 2018, over 210 spacecraft were launched into interplanetary trajectories or towards Lagrange points in the Solar System and were often accompanied by one or two upper stages from the launch vehicle [3]. Currently no dedicated space surveillance system is in place to track these artificial objects after they have performed their mission. There are COSPAR and ESA regulations [4] in place w.r.t. the disposal trajectories of such artificial objects in interplanetary space coming from planetary protections requirements, which aim at preventing biological contamination of celestial bodies. In case of space missions to Lagrange points of the Earth–Sun and Earth–Moon systems, the orbital dynamics induce a non-negligible risk of being captured again in the Earth gravitational system and hence most space debris mitigation requirements apply [5].

The limited implementation of dedicated disposal strategies in heliocentric orbits and the absence of systematic tracking has the consequence that artificial objects are often detected by surveillance systems dedicated to NEOs. It is common that also well-known objects in Earth orbits with large semi-major axis, and/or with large eccentricities, are '(re-)discovered' in this way. In at least three cases objects were discovered and later identified as being artificial rather than an NEO. The most commonly used metrics to tell the two categories apart are the area-to-mass ratio derived from long-term orbit determination on the object and the Johnson-Cousins photometric system (B, V, R, and I). For both metrics we investigate at SDO what can be expected from artificial objects.

There are two relevant classes of artificial objects left in heliocentric orbits: scientific spacecraft and the upper stages used to overcome the Earth's gravitational potential. For both classes, their expected area-to-mass ratio can be estimated from the design information under the assumption that the object is randomly tumbling in space.

Figure 1 summarises the area-to-mass ratio histogram for nearly 6 000 upper stages launched into space until 2018. The mass is the dry mass and the area is the average value assuming random tumbling. In case of spacecraft, there is more variability in area-to-mass ratios in general and classes can be distinguished. However when we limit ourselves to spacecraft which might appear in interplanetary space only the following designs remain: civilian scientific platforms and planetary missions. As is shown in Figure 2, both classes behave rather similarly when compared in terms of mass and area. Figure 3 summarises the area-to-mass ratio histogram for planetary exploration spacecraft. For both spacecraft and upper stages it is clear that the area-to-mass ratio is orders of magnitudes above what would be expected for small asteroids.

Determination of the area-to-mass ratio in the orbit determination process might not be sufficient as metric to distinguish natural from artificial objects. However, a photometric system of colour band filters can be employed here. Various studies have taken place in the last decade to exploit photometry and spectroscopy of artificial objects, both under laboratory conditions and in orbit, to facilitate object fingerprinting for both intact satellites as well as deriving the material composition of fragmentation debris [6,7,8,9]. Most of such studies have focused on intact objects as well as fragmentation debris in or near Geostationary orbit (GEO). An over-arching conclusion spanning multiple studies is that observationally, artificial objects tend to be redder than the Sun. Moreover, experimental analysis suggest that chemical reactions taking place on common spacecraft materials such as Multi-Layer Insulation after prolonged periods in orbit lead to a darkening and reddening of the observed objects [10]. One notable exception to the general rule is however the case of solar panels when exposed to the observer, which are notably bluer. Lab measurements to characterise on-ground the spectral and photometric response of the constituents of spacecraft have taken place and show large uncertainties due to the complexity of the components, e.g. electronic boards [11]. In Figure 4 the data reported in various references is combined to give an overview of the spread possible for artificial objects.

A third option to facilitate the identification of artificial objects is the orbital dynamics of those objects. Whereas the translational motion of heliocentric orbits perturbed by the Earth-Moon system can be chaotic, some motion such as the capture/departure of an object in the Earth-Sun system via the Lagrange points is well understood and even used for mission design. In such cases, the backpropagation of observational states can indicate when an object came close to the Earth as likely point of departure. Moreover, such orbits are unlikely to be populated by natural objects given the age and stability of the Earth-Moon system (but they exist).

The first tentatively identified artificial object to visit the Earth again after being in heliocentric orbit for approximately 32 years was J002E3. The unusual orbit and subsequent spectral analysis identified the object as the S-IVB third stage of the Apollo 12 Saturn V [12].

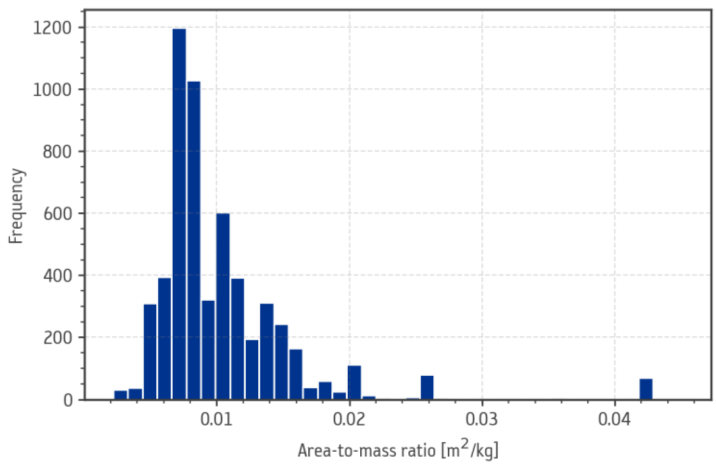

Figure 1. Area-to-mass histogram for all upper stages left in Earth orbit between 1957 and 2018

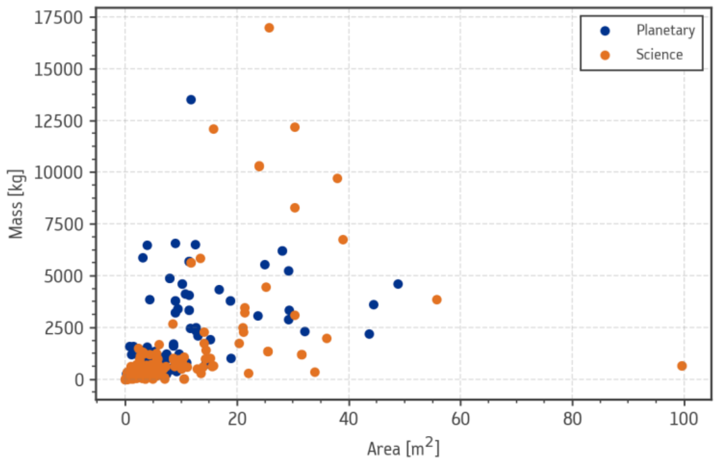

Figure 2. Area and mass scatter plot for civilian spacecraft with a primary mission objective science (blue) or planetary exploration (orange)

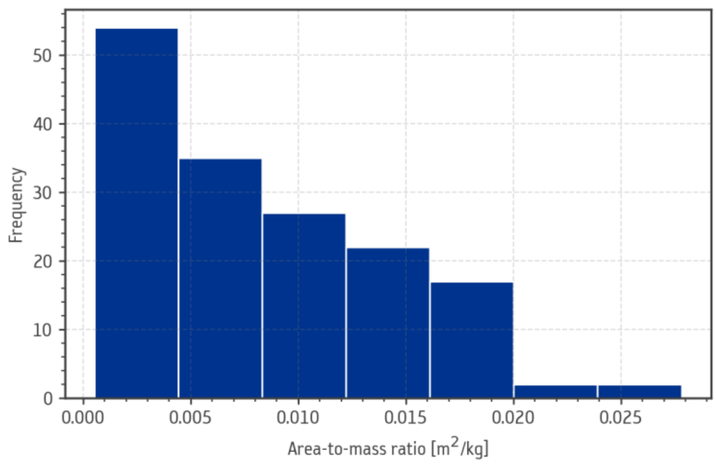

Figure 3. Area-to-mass histogram for spacecraft designs launched between 1957 and 2018 representative for interplanetary missions

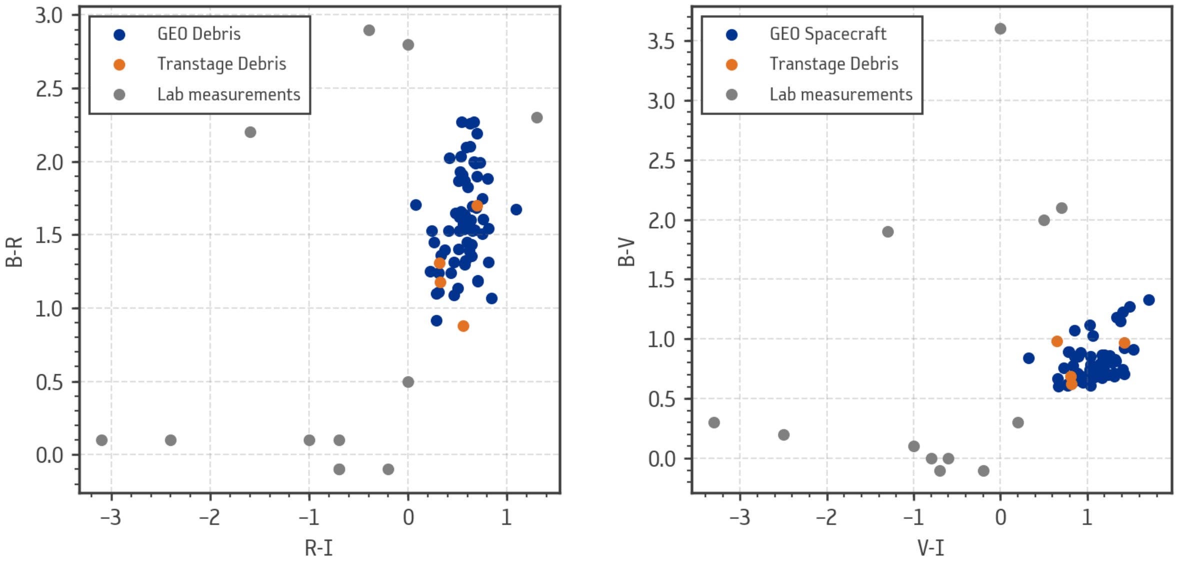

Figure 4. Colour-Colour plots indicating the range of measurements expected for artificial objects as found in GEO. Value for GEO Debris are adopted from [9], GEO Spacecraft from [8], Transtage Debris from [7], and Lab measurements from [6]

A similar encounter took place in 2010, the heliocentric orbit of 2010 KQ got perturbed by the Earth-Moon system. Also in this case did the combination of orbital dynamics and photometry pointed in the direction of an artificial object, in this case an upper stage of a USSR moon probe [13]. Other curious cases, such as 6Q0B44E, exist but the verdict between artificial or natural has not been conclusive.

4 WT1190F OBSERVATIONAL CASE

ESA's NEOCC first observational experience with an artificial body begun in October 2015, when an object discovered by the Catalina Sky Survey and provisionally designated WT1190F turned out to be orbiting the Earth [14]. Subsequent observations, obtained over the next few weeks by a large number of observers and teams, showed two unexpected behaviours:

- From the observed non-gravitational acceleration and attributing it to solar radiation pressure, we could determine that it had an unusually high area-to-mass ratio (AMR), roughly 0.01 m^2/kg, about 100 times larger than what is typically seen on asteroids of this size,
- The perigee of the object was very low, and a collision with our planet was about to happen, about one month after discovery.

The high AMR of the object was strongly suggestive of an artificial origin, being compatible with a hollow shell, or a thin layer of material. We therefore expected a debris re-entry. However, the dynamics of the impact, in terms of velocity and impact angle, was more akin to the impact of a natural object. Therefore, we decided to use this opportunity as a test case to "train" our observational resources for a future natural impactor.

The very first type of observation that is needed to characterise an object and its origin is certainly astrometry. In this particular case, we contacted a variety of collaborating observatories asking for optical imaging of the object, providing them with an accurate topocentric ephemeris tailored to their needs. Thanks to our network, we were able to obtain astrometric coverage from shortly after discovery to less than an hour before the impact of the object with Earth, covering in total an interval of 35 days. The last part of the orbit, when the spacecraft was within 34 000 km of the surface, could be as well observed by ground based radar one day prior to its entry.

The coverage of the last night before impact was especially challenging, due to the high angular speed of the object's motion in the sky. Dedicated observations for the entire night were obtained with the help of the Lumezzane observatory in Northern Italy, from which we could track the entire incoming trajectory starting when the object was about 100 000 km away, up to when it was just 15 000 km away from the observatory.

The entire set of observations we obtained during the campaign allowed us to determine the entry point in the atmosphere with a precision of less than 100 m and with a timing accuracy better than a second. In addition to the observations from discovery to impact, our team was also able to identify prediscovery detections in the Pan-STARRS image archive. The astrometry obtained from these images showed that the object had already been discovered by the Catalina Sky Survey multiple times in the past, as far back as 2013 and possibly even in 2009.

A second important observation to characterise WT1190F was the determination of its lightcurve. Interestingly, up to the days before close approach no noticeable variation of its lightcurve could be measured, neither by our team nor by other observers. The reason for this difficulty became clear during the night before impact, when the object was seen to be an extremely fast rotator, with a peak-to-peak lightcurve period of less than 0.75 seconds (corresponding to a true spin period of less than 1.5 seconds). Such a rapid lightcurve variation had been averaged out in all the observations obtained earlier during the campaign, when exposure times needed to detect the object had to be significantly longer than the period.

A third important element of a characterisation campaign is a taxonomical classification of the object. To obtain a good spectrum of the object, despite its faintness, we submitted an urgent Director Discretionary Time (DDT) request to ESO's Very Large Telescope, and were awarded 30 minutes of observing time. The optical spectrum we obtained showed the object to be slightly redder than the Sun, and with a featureless spectrum [15]. The derived colour indices of B–V=1.1, V–R=0.67, and R–I=0.64 do fit quite well with the general observed spectra of artificial objects in Figure 4. Moreover, the overall spectral behaviour of the WT1190F is comparable to the spectra derived for J002E3, tentatively identified as the third stage of a Saturn V, as shown in Figure 5.

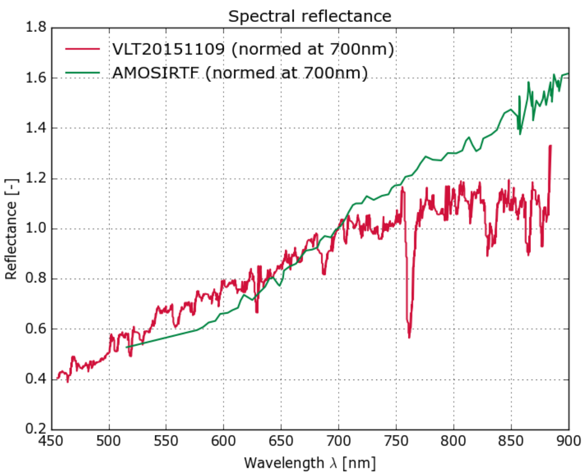

Figure 5. Spectral reflectance for WT1190F (red) and J002E3 (green, [12])

WT1190F returned to Earth on an eccentric orbit with an entry speed of 10.61 km/s, relative to the atmosphere at 100 km altitude, and an entry angle of 20.6º. This re-entry was observed in-situ by an airborne campaign set-up by the International Astronomical Center in Abu Dhabi and the United Arab Emirates Space Agency. The main fragmentation event was estimated between 58 km and 45 km in geodetic altitude and TiO molecular emission bands and hydrogen alpha emission during a disruption of one of the fragments were observed [14].

The opportunity to observe this re-entry event was important for various reasons, one being the fact that the re-entry conditions are most comparable with the re-entry of a natural object. Common conditions for the re-entry of an artificial object are velocities of around 7-8 km/s, relative to the atmosphere at 110 km altitude, and an entry angle near 0-0.2º.

In the first place, it provided an opportunity to test and calibrate sensors which provide spectrographic data of the destructive break-up of artificial objects when they re-enter the atmosphere [16]. Secondly, it provided further circumstantial evidence that the object was indeed artificial in nature. The re-entry spectra of artificial objects often exhibit the emission bands of aluminium oxide, which can mask other lines and bands. The fact that TiO was observed for at least one individual bright fragment points towards the association of WT1190F with a free flying component of titanium. This could for example be a titanium alloy tank with molten attachment points. A candidate object is the Trans-Lunar Injection stage of NASA's Lunar Prospector mission, which is essentially a STAR 37FM solid rocket motor engine with extended functionality. In [17] another alternative candidate, Snoopy (the Lunar Module of Apollo 10), is identified as well. The question which naturally arises is: how to find out which of the two candidate objects re-entered on the 13November 2015 as WT1190F? This question is addressed in [17] based on the collected photometric data while in orbit, but no firm conclusion was drawn.

In order to contribute to a possible identification, we further analysed the re-entry data. We would like to point out that the low amount of fragments observed during the re-entry break-up phase is uncharacteristic for an artificial object at super-orbital speed as witnessed during the re-entry of the Hayabusa spacecraft in 2010. Hundreds of individual fragments were observed, for a parent spacecraft of about 500 kg, whereas for WF1190F this was tens at most. As most of the outer shell of Snoopy consisted of aluminium sheets of a few millimetres, mounted on essentially a rocket engine, heavy fragmentation would have been expected. We thus use the break-up behaviour itself as argument for a more compact and small object such as the Trans-Lunar Injection stage.

Not only the break-up itself is important, but also the orbital trajectory bears pertinent information. As discussed above, the orbit of WT1190F could be refined by identifying the object in observations back until 2009. Propagation to earlier epochs leads to orbits which come so close to the Moon that a single reference trajectory is no longer possible as the induced perturbations are highly sensitive to the input conditions. We thus know where the object was more than 10 years ago and we can ask the question how likely it is that one of the candidate objects would end up in such an orbit. Indeed, just as for orbits around the Earth-Sun Lagrange points, objects in heliocentric or selenocentric orbits have a non-zero Earth atmospheric re-entry probability. The method developed in [18] can be applied to study the long term evolution of the Trans-Lunar Injection stage and Snoopy. In case of the Trans-Lunar Injection stage the point after separation of the payload is taken as starting point. In case of Snoopy a starting epoch and state is sampled from a 4 day orbit arc after its disposal manoeuvre, as reconstructed by NASA. Respectively 10 000 and 15 000 propagations were executed and analysed for both objects spanning at most 100 years, which allows to reconstruct an empirical distribution function on orbit type and time until Earth impact.

The results at the end of the simulation are categorised in the following orbit types: Heliocentric, Earth Sphere of Influence (SOI), Earth Resonance, Earth Impact, Moon SOI, Moon Resonance and Moon Impact. As can be seen from Figure 6 and Figure 7, while an Earth impact is a possibility for Snoopy (~ 0.0027%), it is more likely in the case of the Trans-Lunar Injection stage (~ 0.0155%). Moreover, the Trans-Lunar Injection stage remained most likely in a Moon resonance orbit whereas for Snoopy a capture from a heliocentric into a geocentric orbit would need to be postulated to explain the observations. As shown in Figure 8 and Figure 9, both objects have a likelihood of re-entering on Earth in 2015 although the probability is ~9 times lower for Snoopy. From the orbital and break-up analysis, one would thus be more inclined to identify WT1190F as the Trans-Lunar Injection Stage.

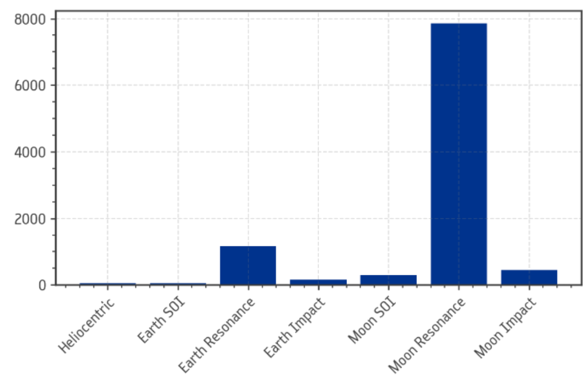

Figure 6. Classification of orbit or impact of the Trans-Lunar Injection stage 100 years after payload separation

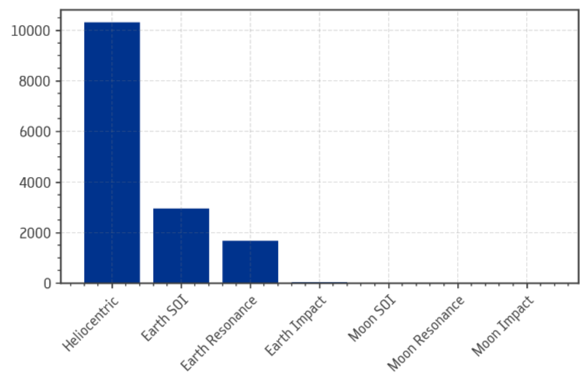

Figure 7. Classification of orbit or impact of the Apollo 10 Lunar Lander (Snoopy) 100 years after its disposal manoeuvre into heliocentric orbit

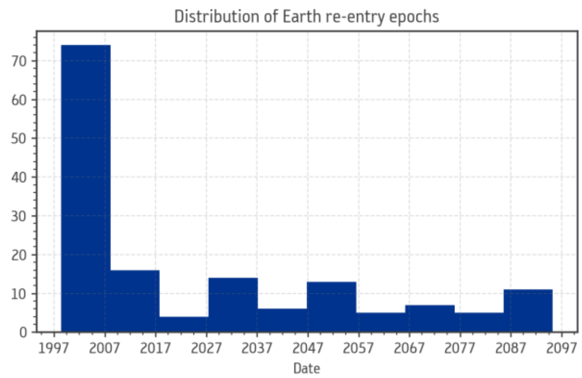

Figure 8. Histogram of the distribution of simulated re-entry epochs for the Trans-Lunar Injection stage (sample size: 10000)

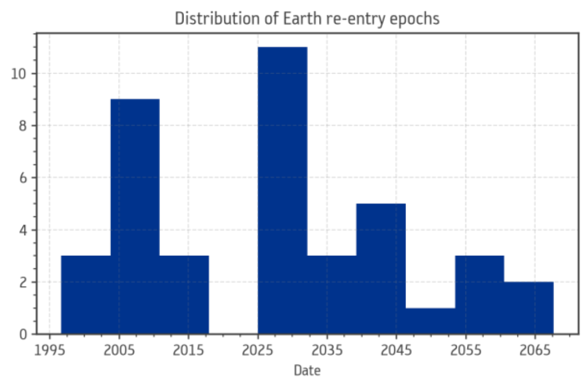

Figure 9. Histogram of the distribution of simulated re-entry epochs for the Apollo 10 Lunar Lander (Snoopy) (sample size: 15000)

5 EXOMARS OBSERVATIONAL CASE

On 14 March 2016 the first spacecraft of the joint ESA/Roscosmos ExoMars programme was launched from Baikonur, by a Proton rocket with a Briz-M upper stage. The flight plan included three complete elliptical orbits around the Earth whilst raising the apogee, before injection into interplanetary trajectory about 12 hours after launch. During these Earth-bound orbits, the spacecraft was in a passive state and did not deliver telemetry to Earth; therefore, the actual trajectory was going to remain poorly known.

A few days before launch we decided to organise an optical observation campaign to track the object during these initial orbits. The size of the object, its velocity and the uncertainty of its position in the sky provided a very good simulation of the scenario we would expect in case of a poorly observed incoming impactor, over the hours just before impact.

Unfortunately, the launch profile implied a very poor observability from the Northern hemisphere, and we had to contact observatories located South of the equator to attempt the observation. Within a few days, we were able to alert and involve about a dozen observatories and collaborators, located at different longitudes in the Southern hemisphere. We provided them with our best guess for topocentric ephemeris, computed on the basis of the expected launch profile provided by Roscosmos.

The first detection was achieved from New Zealand 8 hours after lift-off. About an hour later, another detection was obtained from Siding Spring, Australia, with a telescope of the Las Cumbres Observatory Global Telescope (LCOGT) network. Both these sets of images showed two objects of similar brightness, flying a few arcminutes apart: one of them was identified as the ExoMars spacecraft still attached to the Briz-M upper stage, while the second object corresponded to the depleted and an already ejected auxiliary tank.

The biggest surprise of the observational campaign came a few hours later, when our collaborators at the OASI observatory in Brazil found the Briz-M upper stage. The stage was surrounded by a fuzzy halo, and a handful of much smaller fragments moving at the same speed (see Fig. 10). After investigating this ensemble and based on the modelled reflectivity of both spacecraft and upper stage, we were able to identify it as the Briz-M upper stage, with the debris surrounding it being likely caused by the passivation processes after separation. The observation of fragments that are probably created after separation is not new, but hard to interpret or identify in many instances. In case of the launch of ESA's Herschel and Planck spacecraft, debris was briefly tracked after separation and later identified as most likely ice.

A few other observes worldwide were able to observe the launch hardware independently. In particular, observations from South Africa clearly showed the ExoMars spacecraft flying ahead of the Briz-M, at approximately the same time of the Brazilian set.

All our observations provided astrometric measurements that allowed us to calculate the heliocentric orbit of the object, even without any radio tracking data. The resulting trajectory matched well with the expectations: all objects were found to be travelling toward Mars, with an expected fly-by date within a few days of 14 October, in good agreement with the scheduled orbit insertion date of 19 October.

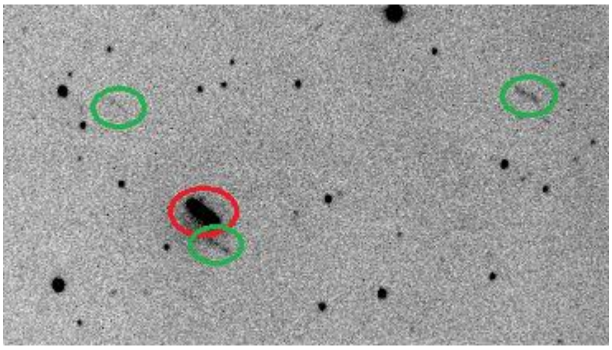

Figure 10. One of the first images from OASI, showing the Briz-M upper stage of ExoMars (inside red circle) and a few debris [Credit: OASI Observatory / J. S. Silva]

6 OTHER OBSERVATIONAL CASES

During our routine observations of NEOs, we also have the freedom to observe man-made objects that have relevance for the NEO observational community, and extract astrometric positions useful for the determination of their orbit.

An interesting opportunity for such an observation happened in September 2017, during the Earth swing-by of NASA's OSIRIS-REx spacecraft. Using ESA's OGS telescope we were able to detect the object when it was still faint, with a magnitude of approximately 21. In this particular case, the ephemeris was very well known from the JPL navigation team, and we could check that our astrometry was in excellent agreement with it, at a level better than 0.2". OSIRIS-REx was also "discovered" a few days later by the ATLAS survey and posted on the NEO Confirmation Page as A10422t, until its identity was noticed and it could be removed.

In March 2018 we also used the OGS to image the Tesla Roadster car launched by SpaceX as the dummy payload for the first test launch of their Falcon Heavy rocket. First detected astrometrically by the SONEAR survey when it was just a couple of lunar distances away, by the time of our observations the object was located at more than 10 million kilometres from Earth and its brightness was close to magnitude 22. Interestingly, rescaling this brightness to the known size of the object proved that what we were observing was actually larger than just the car; the reason for this discrepancy is that the object was still flying with the upper stage of its Falcon rocket attached to the bottom of the car, thus explaining the larger size.

More recently, we also used the OGS to obtain follow-up observations of some small objects that have been discovered as possible NEO candidates by the Zwicky Transient Facility survey. These bodies are all orbiting the Earth with periods of roughly one day, and are all very small, likely a meter or less. Interestingly, they have been found to be extremely sensitive to solar radiation pressure, implying a small mass and a very low density, which might suggest that they are actually pieces of MLI [19].

We used the telescope to obtain astrometry of some of them, resulting in the determination of a more accurate orbit that may prevent them from being lost in the future, and mistaken again as possible new NEOs.

7 CONCLUSIONS

ESA's NEOCC and SDO teams have successfully tracked a number of objects in the past years that are border cases in their respective fields of expertise. Most of these objects are artificial satellites detected by NEO surveys, but are in heliocentric or geocentric orbits that are much higher than most of the catalogued space debris.

Examples where the NEOCC was involved in observations of artificial objects were the return of WT1190F, the launch of the ExoMars 2016 mission, the observation of the Tesla Roadster, and the Earth swing-by of NASA's OSIRIS-Rex spacecraft. The use of ESA's OGS telescope by both teams has been paramount in studying these cases. By bringing together the different methods and techniques used by the two teams allowed a better assessment of the respective situations.

We have focused in particular on the case of WT1190F. Not only astrodynamical methods were used to determine its origin, but also spectroscopic measurements during its re-entry which gave hints about the materials that were observed to burn up.

The underlying synergies in the operation of the two ESA teams allow an effective assessment of objects that are neither an NEO nor a typical space debris. Based on the experiences described in this paper it will be possible to quickly identify future border cases and efficiently analyse them in a team effort.

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