

NEO ROCKS

Near Earth Object Rapid Observation, Characterization and Key Simulations

WELCOME TO THE NEOROCKS PROJECT! NEWSLETTER – FINAL EDITION

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PROJECT FUNDED BY EU H2020

NEOROCKS MAGAZINE FINAL ISSUE – EDITORIAL

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Welcome to the final issue of the NEOROCKS newsletter, for insights into the world of Near Earth Objects (NEOs).

The NEOROCKS project is coming to an end and we are proud to present some of our results.

We started our project in January 2020, full of enthusiasm and ideas. We were stopped immediately by the pandemic. The launch of our project saw all of us at home, the telescopes closed and having to find new ways of working remotely that could guarantee achievement of the goals we had set for NEOROCKS. It was not easy, but we managed. 14 partners from 7 European countries have worked together over the past 3.5 years, with support from the European Commission thanks to a 12 month extension. We implemented a project that included:

- i) orbit characterisation and prioritisation of physical observations;
- ii) new data acquisition in several observing techniques and analysis of data coming from major public surveys; and
- iii) the creation of a unique NEO physical properties database, which includes both orbital and physical properties.

Within NEOROCKS, more than 600 Near Earth Objects have been observed for the first time. The list of observed targets includes the binary asteroid Didymos. It was the target of the NASA mission DART and was observed in situ by the Italian cubesat

LICIACube. We have experimented for the first time a rapid response using a European telescope network performing quick physical characterisation of targets selected by real-time, highly-automated new astrometric observations.

NEOROCKS was possible thanks to close collaboration among all our partners, the Neorockers. NEOROCKS has provided an incredible test of how far and how fast we can go in traversing the whole NEO risk assessment chain, from discovery to physical characterisation, relying on existing European resources and expertise in space surveillance and astronomical observations.

As a heritage, NEOROCKS leaves a strong, cohesive team, which will continue to coordinate activity in the future. Another enduring heritage of NEOROCKS is a state-of-the-art NEO physical properties database, which will be permanently hosted at the ASI Space Science Data Centre (SSDC). It has been designed following the IVOA (International Virtual Observatory Alliance) guidelines, which improve the availability and interoperability of astronomical data through adopting the EPN-TAP (EuroPlaNet Table Access Protocol) standards and the FAIR (Findable, Accessible, Interoperable, Reusable) principles. Once migrated into ASI SSDC, the database will be open to external users with the ambition to becoming a worldwide reference data source on NEO physical characterisation.

NEOROCKS shows that Europe can play a prominent role in NEO monitoring and alert systems. We have an internationally recognised NEO scientific community and a huge availability of assets: skilled observatories, large telescopes managed by national or international consortia, advanced orbit determination and impact monitoring systems.

I am proud and honoured to have coordinated this important project and to share with you some of our results and ideas, in this last issue of the NEOROCKS newsletter.

Last but not least, NEOROCKS has given us the chance

to revisit Tumbling Stone, an important source of information about asteroids. As Livia Giacomini tells us in her article in this issue, Tumbling Stone was discontinued, but its content is too important to end up in the archives. We have revisited some articles in our newsletters and launched a new [Tumbling Stone page](#) on our website. We will publish articles regularly over coming months (there are many of them!) so keep checking back in.

Happy reading!



PRIORITY LIST, TARGET OPPORTUNITY LIST AND PRECOVERY Tools to support NEO orbit determination improvement

Fabrizio Bernardi
Space Dynamics Services S.r.l, Italy

The NEOROCKS has sought to provide observers with tools that facilitate their work in understanding Near Earth Objects (NEOs).

A physical characterisation observation is necessary to understand the physical properties (material composition and properties, rotation status, shape, etc.) of target NEOs. However, before doing this, observers must consolidate their knowledge of dynamical properties. In other words, we need to know more about their orbits. Recently discovered NEOs have limited data and the orbit determination is generally poor. With more data, it is possible to predict their position in the sky with more accuracy. In order to increase efficiency of this orbit determination process, the Neorockers have developed a set of tools to support observers, both professional and amateurs, who wish to provide astrometric data (targets' positions in the sky) to improve orbit knowledge.

These tools include:

- The Priority List;
- The observations prediction tool;

- The target opportunity list;
- The NEOCP priority list;
- The Follow-up Ranking.

NEOROCKS has also undertaken extensive precovery activity.

Let's find out more about each of them, in turn.

PRIORITY LIST

This tool provides a list of known NEOs, which are visible right now and require so-called "follow-up observations".

They are listed according to a priority value, which is computed by taking into account orbit uncertainty, visibility window and urgency to be observed, level of risk (NEOs that risk hitting the Earth in the next century) and further technical parameters. This Priority List follows an idea developed some time ago by the team at the IAPS-INAF institute (Boattini, D'Abramo, Carusi and Valsecchi). Around two decades later, this algorithm has been reviewed and improved to support both professional and amateurs observers in following-up NEO targets.

ID	Name	Date	RA	Dec	Magnitude	Priority	Risk	Technical
2005 YU55	2005 YU55	2005-12-16	10h 48m 00s	+16° 51' 00"	18.5	High	Low	Good
2008 TC3	2008 TC3	2008-10-07	22h 03m 00s	+34° 39' 00"	18.0	High	Low	Good
2009 CR	2009 CR	2009-02-28	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2010 TC7	2010 TC7	2010-09-27	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2011 AG	2011 AG	2011-04-10	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 BA	2012 BA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 DA	2012 DA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 FC	2012 FC	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 GA	2012 GA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 HO	2012 HO	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 LA	2012 LA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 OR	2012 OR	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 QA	2012 QA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 RA	2012 RA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 SA	2012 SA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 TA	2012 TA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 VA	2012 VA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 WA	2012 WA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 XA	2012 XA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 YA	2012 YA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good
2012 ZA	2012 ZA	2012-06-13	10h 00m 00s	+34° 39' 00"	18.0	High	Low	Good

Figure 1 - Priority List output example

The Priority List is updated regularly, at least once a day when new data are processed. It is also possible to request a specific mailing service, which sends emails automatically with a customised version of

the Priority List that takes into consideration the telescope limiting magnitude and the declination range.



Figure 2 - Priority List customised email service example

The purpose of this tool is to drive observers toward observing targets whose orbit needs to be consolidated as soon as possible. The overall goal is to maximise general efficiency of the surveying system.

The Priority List is [available here](#). There is also a [version for fainter targets](#), supporting observers that have bigger telescopes from 1 meter and above.

THE OBSERVATIONS PREDICTION TOOL

This tool provides data and a sky map to predict the position of an asteroid in the sky for a specific observing station, at a specific time. It outputs the position in the sky (right ascension and declination), the magnitude (how bright it is), the motion speed and direction and the region of uncertainty (i.e. where we are supposed to detect the target).

A plot with background stars facilitates detection on

real sky images. The NEO target should be detected within the red ellipse and it should move along the direction of the green arrow as in Figure 3 .

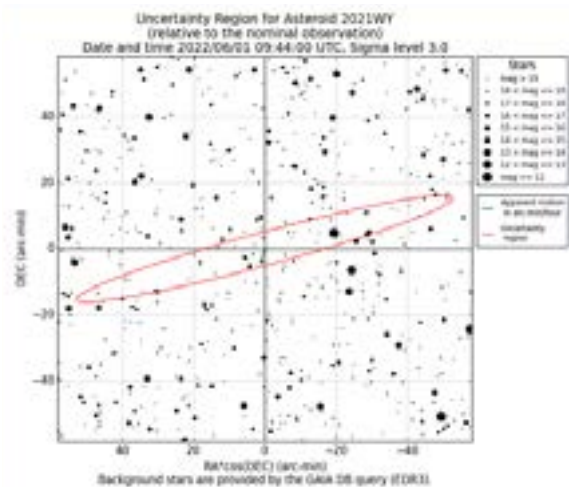


Figure 3 - Observing Prediction Tool sky plot for NEOs

A similar tool is provided for those objects in the NEO Confirmation Page (NEOCP) of the International Astronomical Union’s Minor Planet Centre. These are typically NEO candidates that have just been discovered and they usually have limited data for a very short arc. For example, targets just-submitted to the NEOCP can have as little as half an hour of arc. This means that the orbit is very poor and may mean that the orbits that are either very close or very far away.

Therefore, it is important that observers around the

world observe and detect it as soon as possible, so that the orbit can be constrained and the discovery Minor Planet Electronic Circular released. In this phase, the possible position of the target in the sky may cover a large region. The region of uncertainty, where the object may be detected, is not regular and may have complex, folding fan shapes. Moreover, the visual magnitude (how bright the target should be at any given time), can vary a lot within the uncertainty region.

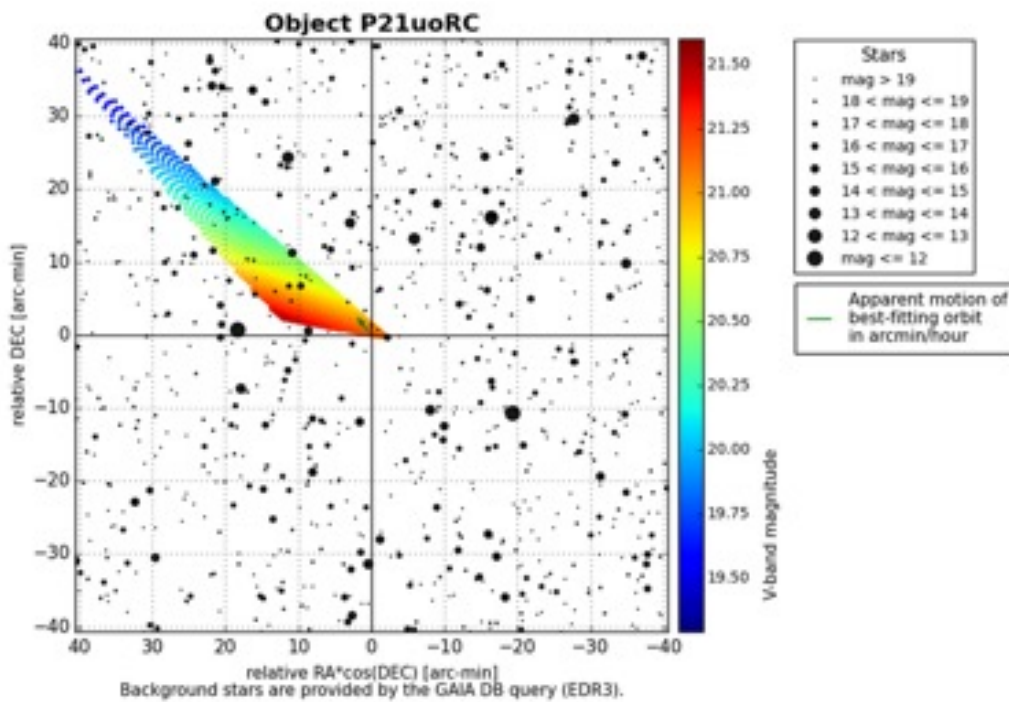


Figure 4 - NEOCP target sky plot example

The tool can be set to plot other information, such as the family belonging and the MOID (Minimum orbit intersection distance). Should an object in the NEOCP pose any risk of hitting the Earth within the next month, this tool allows us to plot the region (in full red circles) of the possible impacting solutions

(Figure 5). The observer can focus only in that region in order to confirm or otherwise the impact.

THE TARGET OPPORTUNITY LIST

This tool provides a list of observable NEOs for the next year. The output list can be filtered according to a series of parameters, which include the maximum visual magnitude, uncertainty size, presence or otherwise of the risk list.

This tool is designed particularly to support professional observers, when they have to plan the list of targets to be observed several months in advance, for example when preparing a telescope proposal.

The [full list is available here](#).

THE NEOCP PRIORITY LIST

The NEOCP priority list provides a list of targets in the Minor Planet Center (MPC) NEO Confirmation Page according to a priority determined, in practice, by observability constraints (visual magnitude and uncertainty size, mostly).

This will help observers when choosing their targets for follow up from NEOCP and, among other positive results, can limit wasted telescope time.

The service [can be found here](#).

FOLLOW-UP RANKING

This service provides ranking tables of observatories, which have provided useful follow-up observations. The purpose is to find a way to award the efforts of observers that dedicated time to improve the observed arc length of newly discovered NEOs or NEOs at following apparitions, after the MPEC publication.

The Priority List Value algorithm seems to be a good metrics of the contribution that a measurement provides to the data quality of the observed NEO. The basic idea is to compute the Priority List Value before

the orbit determination of the new measurements, and after. The difference is attributed to the first observer of the data set. If there are other contributing observers of the same dataset (for example, when there is a recovery MPEC), credits are also allocated to the other observers, but halving the attributed score.

In this way, it is possible to build ranking tables that are updated regularly as soon as there are new data. The tables are divided into two sections: yearly tables and lunation tables, which are computed on a yearly basis or during the present lunation. Each section presents three tables: the Overall ranking, the Big Survey ranking, and the other observers ranking. In this way, the tools give appropriate visibility to small telescopes observers (typically amateurs) that spend a fair amount of time on this important activity. Big surveys, of course, have much more observing capability and they can perform follow-up observations more easily.

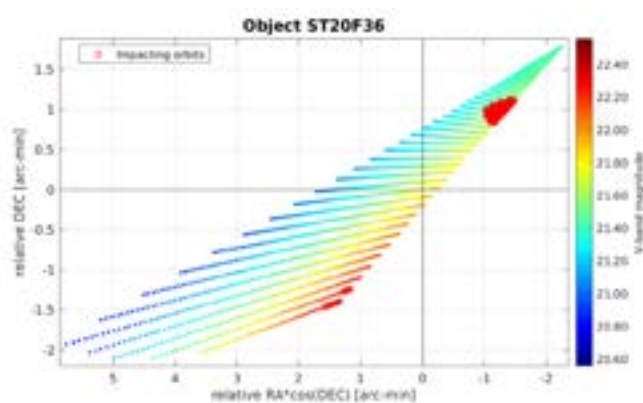


Figure 5 - NEOCP observing prediction plot with possible impacting solutions



Figure 6 Follow-up Ranking page example

After each lunation or at the beginning of the next year, we send a report to the Minor Planet Mailing List showing the ranking tables and pointing out the most successful observatories and NEO recoveries. With this tool, we want provide the community with a systematic and independent way to measure the performance, which can be used as a reference when writing grant proposal or searching for funding. The benefit is to increase the motivation to perform follow-up observations.

PRECOVERY

The precovery activity consists in searching in image databases for those images that depict when a just-discovered NEO might have been imaged but not yet detected. This is particularly important when dealing with NEOs with a potential risk of impacting on Earth in the future. With further data dating back few months or even years, it is possible to constrain the orbit solution and to locate better the position of the NEO in space. Neorockers have developed an automatic system that considers updated information coming from MPC (new objects

or updated data for known objects) on a daily basis. In this way, we can scan the image database of the Canadian Astronomy Data Centre service (<https://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/ssois/>) promptly and more efficiently. When one or a set of images is selected, they are checked for faint trails of our target. We measure it and submit to the Minor Planet Center.



OBSERVING NEW BINARY NEAR-EARTH ASTEROIDS IN NEOROCKS

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Binary asteroids (i.e., asteroids with satellites) are a particularly interesting class of Solar System bodies. They are natural “laboratories” where we can study formation and evolutionary processes, both gravitational and non-gravitational, working in asteroids. Moreover, their observations lead to determination of some asteroid properties (e.g., bulk density) that are difficult to obtain by other means. As such, they are of a particular interest within the NEOROCKS collaboration.

One of the most powerful methods of detection and studies of binary asteroids is the technique of time-resolved (lightcurve) photometry. With it, we observe so-called mutual events between the two bodies of a binary asteroid system. The mutual events, which are actually mutual occultations and/or eclipses between the two bodies, are derived from measured lightcurve photometry data using the method of lightcurve decomposition (Fig. 1). They manifest themselves in the data as periodic brightness attenuations that repeat with a half of the mutual orbit period, as the two bodies become aligned with the Earth or the Sun twice during each orbit period. (So, we observe there two kinds of events, the primary and the secondary events, depending on which body is being occulted or eclipsed at a given orbital phase.) Data for mutual events taken over a range of different viewing and illumination geometries (which typically require years to obtain)

then allow us to model the full mutual orbit of a studied binary asteroid system (Fig. 2), and also to reveal its possible secular evolution (which is caused by the interplay between mutual tides of the two bodies and the non-gravitational thermal Binary YORP effect acting on the binary asteroid system).

Among nearly one hundred NEOs for which we obtained lightcurve photometry data within the NEOROCKS collaboration by June 2022, we have discovered 7 new binary systems.

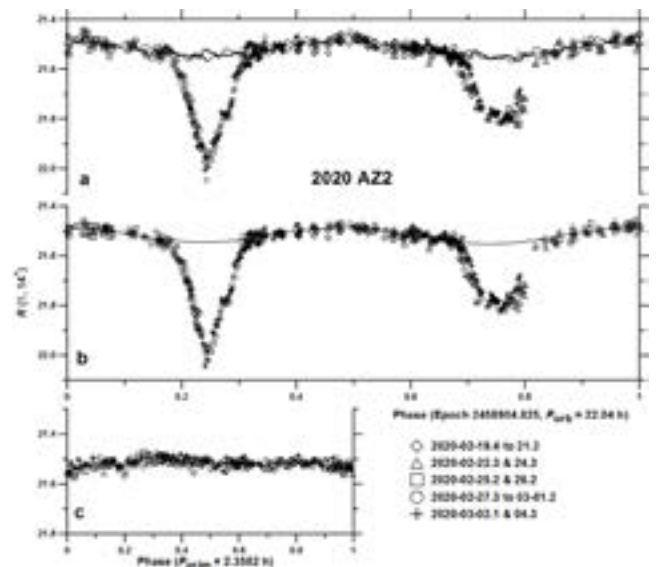


Figure 1: Full lightcurve data of a binary asteroid (panel a) are decomposed into the orbital lightcurve component (panel b) showing the rotational lightcurve of the satellite (the low-amplitude curve) and the superimposed mutual eclipse/occultation events between the two bodies (the deep minima around orbital phases 0.25 and 0.75), and the low-amplitude rotational lightcurve of the fast spinning primary (panel c).

They are following NEOs: (31346) 1998 PB1, (143649) 2003 QQ47, (326732) 2003 HB6, (350751)

2002 AW, 1999 RM45, 2013 PY6, and 2020 AZ2. (We have published their discovery observations in following circulars: CBET 4978, 5037, 5039, 5110, 4931, 4891 and 4728, respectively.) They were discovered with our two primary instruments that we use for the lightcurve photometry studies of NEOs: the 1.54-m telescope on La Silla Observatory and the 0.65-m telescope on Ondřejov Observatory. In addition, we have also observed two binary NEOs, (85628) 1998 KV2 and (539940) 2017 HW1, that were independently discovered a few days before our observations by Brian Warner (published on CBET 4757 and 4771, respectively).

Each time we discovered a new binary NEO, we informed other members of the NEOROCKS consortium and asked them to take additional observations of the new binary using their specific observational techniques. This strategy was to obtain more information for the studied binary

NEOs, which would allow us to get better models and a more thorough understanding of the binary asteroid systems. Very important contributions were provided by the teams led by Julia de León and by Colin Snodgrass. In particular, they obtained spectral or colour observations for 7 of the 9 binaries, from which we determined or constrained compositions of the binary NEOs. That also allowed us to get better estimates for sizes of the binary systems, by constraining their geometric albedos for their specific compositional types. The collaborating teams also obtained additional photometric observations for 4 of the 9 studied NEOs, extending their observational coverage which will allow us to construct their more precise models. In a few cases, we succeeded to obtain complementary observations also from other observatories outside the NEOROCKS consortium; these wider collaborations turned out very fruitful as well.

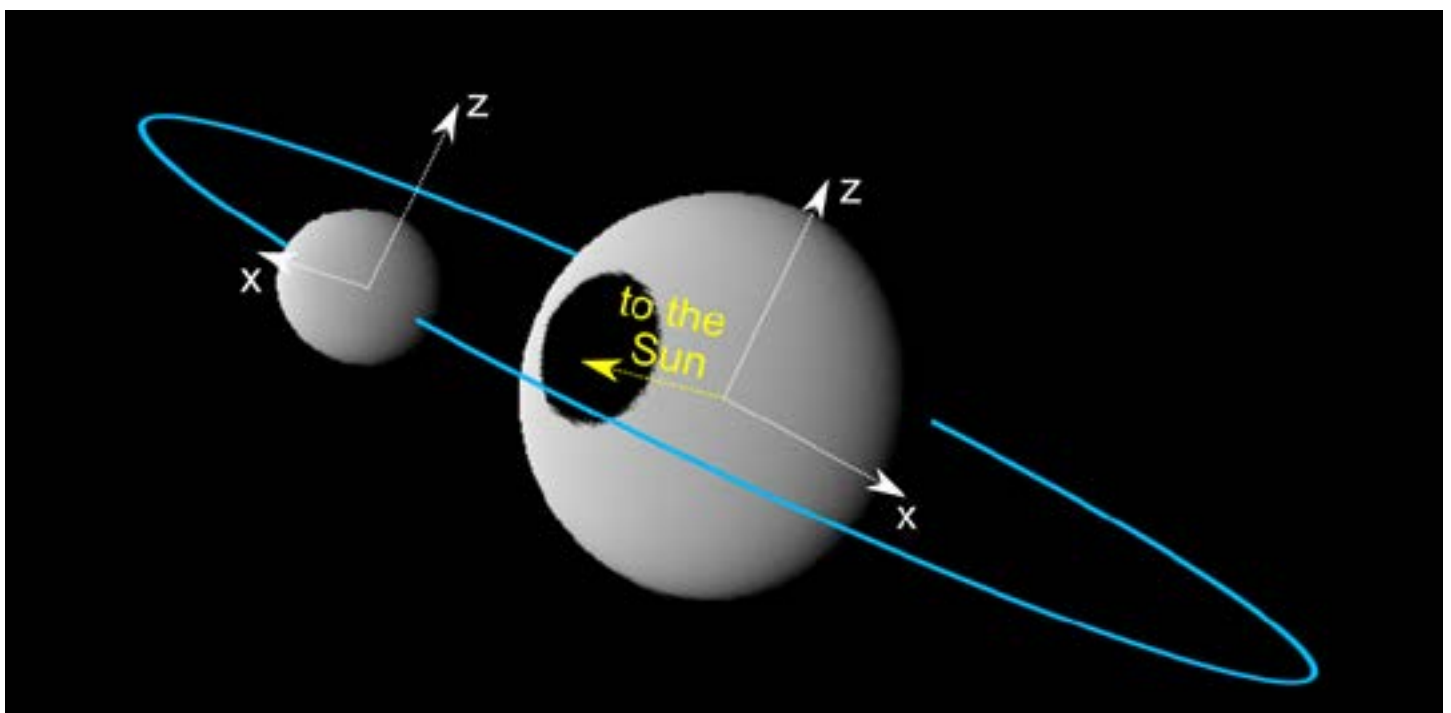


Figure 2: Model of a binary NEO, constructed from observations of mutual events taken in a few observational apparitions (over a few years).

In Table 1, we present basic parameters of the nine binary NEOs that we studied. It shows that the binary NEOs share certain common characteristics; some of them are due to specific formation and evolutionary mechanisms working in NEOs. In following, we highlight some most interesting features and mention how they are related to the binary NEO properties and formation/evolutionary processes.

The primaries (main bodies) of the observed binary NEOs have diameters from 140 metres to nearly 2 km. While the apparent upper limit is not statistically significant - our observed NEO sample contains few bodies larger than 2 km - and does not have a physical meaning, the lower limit is significant. It coincides with the transition diameter, which is about 150 metres, between larger asteroids with low or zero cohesion that are held together by self-gravitation (and probably have a rubble pile structure) and smaller asteroids with non-zero cohesion that are in the strength regime (having probably a more solid structure). Only asteroids with the weak, rubble pile structure can readily form satellites by the process of spin fission or mass shedding, which is a predominant binary asteroid formation mechanism. Therefore, we do not find binary systems among NEOs smaller than about 140 metres.

The secondaries (= satellites) are substantially smaller than the primaries of the observed binary NEOs. The diameter ratios range from 0.21 to 0.53, which correspond to the mass ratios from 0.01 to 0.15 (assuming same density of the two bodies). So, the satellites contain only fractions of total masses of the binary NEOs; binary asteroid systems with near-equal size components are missing or they are

rare. This again is probably related to their formation mechanism by spin fission or mass shedding, where only a small part of the main (primary) body is „lifted“ and forms a satellite.

The observed binary NEOs are relatively close systems with the distances between the two bodies being mostly between 1.6 and 2.7 primary's diameters, with the orbit periods mostly between 13 and 27 hours. While wider binary asteroid systems do exist (as shown by other studies), so there is actually a tail of the distribution to larger a/D_1 values and longer orbit periods, of which we have got one case (31346) in our observed sample, the lower limit on the separation between the two bodies of about 1.5 primary diameter, corresponding to orbit period about 12 hours, is real. It is probably because satellites on orbits closer to the primary (below the Roche limit) would be unstable and prone to break up.

The last characteristic feature that we show here is that the primaries of the observed binary NEOs are all fast rotators with rotation periods in the narrow range from 2.3 to 4.6 hours. Their spins are in fact right below the critical rotation frequency, which is estimated to be about a period of 2.2 h for bodies with typical asteroid densities (about 2 g cm^{-3}), for cohesionless bodies held together by self-gravitation. This is because after the formation of a binary NEO by rotational fission of its parent body spinning at the critical frequency, only a small fraction of the body's angular momentum is transferred to the satellite's orbit and the primary of the formed binary system still spins fast with a period not much greater than the critical rotation period of about 2.2 h.

We continue our photometric observations of binary NEOs within the NEOROCKS project. Our current main aims are to (i) enlarge the sample of studied binary NEOs so that we can draw stronger conclusions about their properties based on a larger statistics, and (ii) re-observe the binary NEOs in their upcoming apparitions so that we can construct their more precise models.

Table 1: Basic parameters of the studied binary NEOs. D1 is the primary's mean diameter, D2/D1 is the secondary-to-primary mean diameter ratio, $a/D1$ is the relative size of the semi-major axis of the mutual

orbit (i.e., the mean distance between the centres of mass of the two bodies), P_{orb} is the mutual orbit period, and P1 is the primary's rotation period.

Binary NEO	D1 (km)	D2/D1	$a/D1$	P_{orb} (h)	P1 (h)
(31346) 1998 PB1	1.0	0.38	4.3	55.40	2.736
(85628) 1998 KV2	1.0	0.28	2.2	21.17	2.823
(143649) 2003 QQ47	0.8	0.33	1.6	13.06	2.645
(326732) 2003 HB6	1.9	0.23	2.4	22.92	3.463
(350751) 2002 AW	0.39	0.21	2.5	25.12	4.647
(539940) 2017 HW1	0.6	0.39	2.6	26.17	2.635
1999 RM45	0.31	0.45	1.9	16.44	3.070
2013 PY6	0.8	0.24	2.7	27.30	3.625
2020 AZ2	0.14	0.53	2.4	22.04	2.358



TUMBLING STONE REVIVAL: KEEP THE STONES TUMBLING!

Livia Giacomini
INAF – National Institute for Astrophysics, Italy

"Asteroids, just as humans, are not all the same. Some of them are very stable, and live their lives without ever straying from their initial paths. Others can be somewhat unpredictable in their choices. And sometimes they can become dangerous."

This is the incipit of one of the first articles I ever wrote. It was year 2001 and I was assistant editor of *Tumbling Stone*, the online monthly magazine co-sponsored by The Spaceguard Foundation and the NEODyS service. As the name suggested, this independent media was founded to inform about NEOs. We can say that it was one of the first attempts to deal at the same time with the science of this topic and with its mediatic impacts.

The words of Andrea Carusi, President of the SGF, explained very clearly our intent: "*Tumbling Stone* is addressed to everybody, although our main targets are journalists willing to understand more, to follow our activity, and to provide the public with reliable, updated and controlled information. We consider this as an important aspect of the international efforts that are being devoted to NEO studies and will do our best to provide enough basic information to follow the current research and their probable future developments."

At the beginning of the century, NEO science was indeed developing quite fast. Many things in those years needed to be explained and discussed within the community, but also outside it. *Tumbling Stone* was like a science communication lab, a place

where scientists and media professionals started to collaborate to find a good balance between science and newsworthiness, to find the right language to communicate impacts and more in general science.



Tumbling Stone did its best to tell in real time the story of space exploration: starting from NEAR landing on asteroid EROS in 2001 up to Stardust flying through the dust atmosphere of comet Wild 2 in 2004. We also had the honour to witness the birth of future space missions, following the transformation of simple ideas into projects that today involve teams of hundreds of people and produce very important scientific and technological results.

Of course, it was not only about science. Politics, economy, war, and many other topics were raised in our monthly pages. Just like the rest of the world, in 2001 we were struck by the news and we witnessed and participated in the lively discussion that assigned the names Compassion, Solidarity and Magnanimity to three newly discovered asteroids in memory of the victims of the Twin Tower Attack.

Risk perception was another topic that the scientific

**ASTEROID (4149) HARRISON DISCOVERED
 IN A PUZZLING ROTATION STATE!**



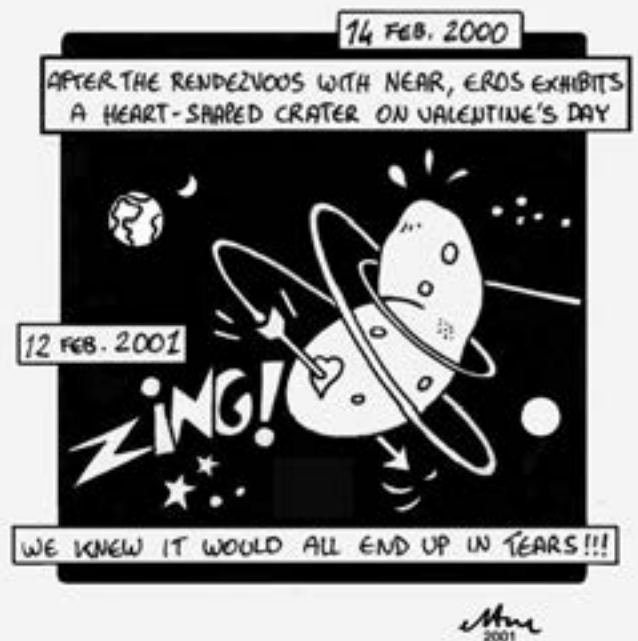
community and the media discussed monthly in Tumbling Stone. Long before films like "Don't Look Up!", I remember events like the deorbiting of the Mir Space Station, when we needed to fight in first person the perception of uncontrolled risk caused by science. At least once a year, we had to publish a "Special Issue" with the scientific story of a first page, ready-to-hit, dangerous rock from space. We had to explain to the media and the general public that - No, we wouldn't be hit in the next months/years by these bodies and that -Yes, we needed to monitor and study them.

We also had the chance to participate in the first political steps in this field of science, like the birth and growth of worldwide collaborations and campaigns to observe and monitor potentially dangerous bodies. There were also political events, like the Congress in which the Palermo scale was introduced to quantify risk related to impacts more effectively. Another was the Workshop dedicated to arise NEOs interest in society organised by OECD (Organisation

for Economic Cooperation and Development) in Italy in 2003.

To make all this come true, Tumbling Stone needed a special editorial staff. Besides myself, the "journalistic soul" behind the project included our editor in chief Nanni Riccobono, an Italian journalist coming from main stream media, fascinated by asteroids and their risk of impact. There was also a team of forward-thinking scientists, who were not ashamed to speak to the public in terms that were meant to be simple, engaging, innovative and sometimes funny. Like Andrea Carusi, Giovanni Valsecchi, of course Andrea Milani, and a young Ettore Perozzi with his very funny Tumbling Laughs. Then, we worked with a number of national and international scientists who were the real strength of the magazine.

Today, Tumbling Stone can no longer be found online and this is a pity. However, as you can clearly see, the community that was born within it and that grew with it, is more active than ever. All those efforts were not useless and I was very happy to learn that NEOROCKS is republishing some of the original content of those years, making it come alive with



new facts, new discoveries, new discussion, new science. In a nutshell, the stories of NEOs can keep on rocking - or maybe we should say, tumbling -, right in these pages!



SCIENTISTS CRITICISE JOURNALISTS FOR THEIR "SUMMER INTEREST" IN NEA HAZARD



TUMBLING STONE REVIVAL: HOW TO LAND ON AN ASTEROID

Andrea Milani

Science fiction novels and movies did play a role in steering the public opinion in favour of space exploration. However, they also gave the misleading impression that landing on another world is easy; more so, when the target is a small body, roughly 500 times smaller than Earth. Since escape velocity is proportional to the size, the approach can take place at a speed more appropriate to a car than to a rocket. But, this neglects four serious difficulties. First, to go down to the surface of the diminutive planet you need to know which way is down. Second, you need to know where you are, and how fast you are going down. Third, you need to be able to slow down in a precise way. Fourth, you need to do have all the information at the right time.

All this becomes apparent when I am back-seat driving, right behind the shoulders of Steven Chesley and Peter Antreasian, in the computer room of the Navigation section at Jet Propulsion Laboratory,

Pasadena (CA). It is 11:19 (Pacific time), they have just received confirmation that the second rocket firing has been completed, and the spacecraft is heading down, in a 5 kilometre free fall. The real time data shown on the computer screen they are watching indicates that the speed of the descent is not exactly as it should have been, according to their computations, but the difference is 800 meters (half a mile) per hour. Anyway, the last time they could do anything to correct the descent was almost one hour ago.

To understand the difficulties the two space navigators, and the entire NEAR team, are facing, you need to take into account that radio signals take 17 minutes to get from the spacecraft orbiting around Eros to the ground stations: the distance is more than double the distance of the Earth from the Sun. If the orbit of the probe is not as expected, a suitable correction needs to be computed, and then

another 17 minutes for the new instructions to be received on board. Even assuming NEAR is capable of immediate reaction, and is not doing something else, like taking pictures of the asteroid, the reaction time for whatever unexpected event is about three quarters of an hour.

Even though the speed of the descent is always below 20 kilometres (12 miles) per hour, it is not at all like driving a car, unless you are driving blindfolded, being informed of where the car was at least 35 minutes ago. If the course was perfectly known, like a car on a very smooth road, this would be not too big a problem. On the Earth, with its shape very closely resembling a sphere, we know where is the direction of the centre of our planet is, because gravity is pointing to it. But the small asteroids, like Eros, have a very irregular shape; thus it is very hard to know where the arrow of gravity is pointing. The spacecraft falls down following gravity, not headed to the centre of Eros. Over 35 minutes, this could amount to a position error of hundreds of meters. Thus, it is difficult to know the position in advance, before it is too late.

After the first descent burn at 6:32, the spacecraft turned to point the main antenna towards the Earth and sent signals allowing to pinpoint its position and rate of descent. Then it turned again, to point the camera towards Eros; after a good 20 minutes of pictures, turned back to point the antenna and send the images back. By the time the data were received at the ground station, and forwarded to JPL, it was 9:20. That was the time the race began: the two orbit computers in the JPL Navigation room had to decide the final correction to be applied to the time of the second burn, and to deliver it to the Mission Operation Center, at the Applied Physics Laboratories in Baltimore (MD) by 10:15. The spacecraft was

falling down at a leisurely speed, but the rhythm of the work was breath-taking: they had to do the computation in time, no use for a late entry, no way to correct later if it was wrong. Orbit determination is a tricky business, as a matter of fact, I have much more experience than the two young men in front of me, but I have never even considered doing anything like that in less than one hour. It can be done, if the computer software has been very well written and tested, and if they do no mistake at all.

I was waiting for the last computed correction in the Navigation room, with Bobby Williams, the leader of the Navigation Team, and most of the others. Pete and Steve arrived there with only a few minutes to spare before the deadline; moreover, their two independently computed solutions were not the same! But the difference was not significant, being less than the uncertainty. Thus Bobby had signed the fax with the instructions for the last minute change: the second rocket burn has to be postponed by 17 seconds, which by the way is a very small correction. When he pushed the send button on the fax, somebody pointed out that this delivery of instructions to the Mission Operation Centre was late by 17 seconds, a nice coincidence.

Less than 10 minutes later Mission Control has sent the signal to the spacecraft. In the meantime, the spacecraft has changed again its orientation, to point the rockets in the right direction, and at 11:00 it has begun the 2 minutes 30 seconds burn. However, by the time we are informed this has indeed happened, at 11:17, it is too late to do any correction: NEAR is going to hit the surface of the asteroid in about half an hour.

Then we can just wait and watch; the data are flowing in in real time, that is, 17 minutes late. The Navigation Room is more and more crowded, at the

end there are more than 20 people, many have video cameras to capture the event, including the tension appearing on the faces of the team, apart from Booby who is remarkably calm. After burn number 3, the spacecraft should be at 3 kilometres (1.8 miles) altitude, but the online data appear to indicate it is too



[Asteroid 433 Eros was the first NEO discovered, back in 1898 and one of the largest of its kind \(30 km in size\). It is also the first asteroid orbited by a spacecraft in 2000, which sent spectacular close-up images of its surface.](#)

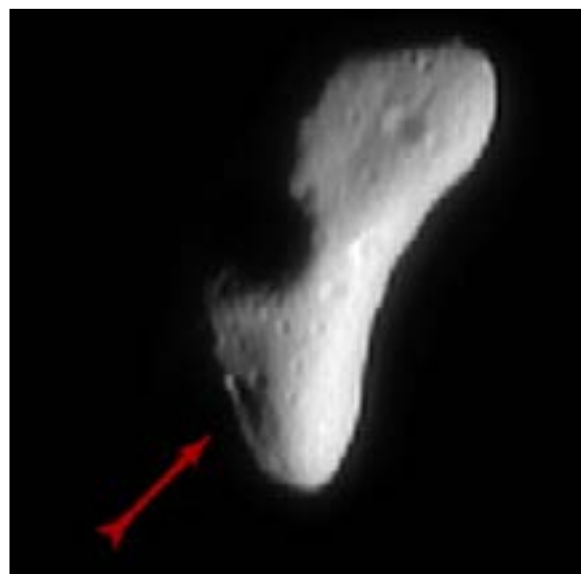
high. This is not good: in space there are no brakes, rockets can be used to slow down the descent, but if they are used for longer than needed the spacecraft could actually start moving upwards, and after the last burn is complete it could fall from far too high, and far too fast.

The tension grows, but in a few minutes the line on one of the screen indicating the altitude appears to approach again the nominal curve. At 11:47 the signal announcing rocket burn number 4 arrives; the altitude monitor says 1.5 kilometres (0.9 miles), the spacecraft has already touched down, but we do not yet know!

At 11:59 the last burn begins; it should end at a few tens of meters above the surface. Now the spacecraft is below 500 meters (0.3 miles), and the images are incredible. More than an asteroid surface,

it looks like a beach with scattered boulders. In the Navigation room at JPL, and in the Mission Control room at APL (Baltimore), which is connected by a real time video, the feeling of triumph begins to show on the faces. But it is not over yet: how fast it is going to hit? And will the spacecraft be capable of surviving and maybe transmitting data from the surface? The last image is 120 meters (394 feet) from the surface, it shows details just a 2 centimetres (.8 inches) across, and it arrives interrupted by the impact: the signal indicating touchdown arrives at 11:02 (Pacific time), only two minutes before the scheduled time. According to Chesley, the impact speed is around 6 kilometres (4 miles) per hour. The rockets were firing the last part of burn number 5 when touchdown occurred, and they automatically switched off, although the control system was not designed to operate during an impact.

This result already appears to be extraordinary, actually better than expected. The descent trajectory, as seen from the tracking data, appears to be so close to the nominal solution that the difference is hard to see in the computer plots. But this is not yet all. The



[Bizarre coincidences accompanied the NEAR-Shoemaker mission: upon arriving on Valentine's day on an asteroid named after the god of love, in one of the first images sent to Earth one could see an heart-shaped feature, an illusion formed by three separate craters under peculiar lighting conditions.](#)



[Close-up view of Boulders on Eros battered surface](#)

probe is still in touch with the ground stations! NEAR has not been designed to work while in touch with the ground, but in fact it is working, maintaining the antenna pointed towards the Earth. At first there is only a carrier, but later it will be possible to receive telemetry and to send telecommands to the probe on the surface. The landing has been so soft that nothing essential broke down.

When they were defining the goals of the NEAR mission, the mission director Bob Farquhar and the other NASA scientists and managers carefully avoided to include the landing as part of the mission definition. A spacecraft built to perform a landing, and to operate even after impact, would have by far exceeded the complexity, development phase duration and cost allocated for a Discovery mission. Landing was a deliberate risk taking, an attempt to do something by far exceeding the specifications.

This gamble has payed handsomely. This success appears to be capable to give back to NASA, to APL, JPL, and many other laboratories across the USA, the confidence they had lost in the last years as a result of a perverse combination of excessive prudence and outright failures. It is appropriate that the NEAR mission was renamed, although in a late stage (to the point that most people still use the old name), to honour Eugene Schoemaker. He was a pioneer of the understanding of the Near Earth Objects and of their relevance for our planet, he was also a man capable of taking risk; in fact while looking for impact craters in the Australian desert he died in an accident, before having had the chance to see these images of Eros. If anything, NASA is now faced with a strange problem. Now that the spacecraft appears to be working quite well on the surface, how will NASA be able to terminate the mission before February 14?



The deadline has nothing to do with Saint Valentine, or maybe it does. NEAR arrived at Eros on February 14, 2000; as gossip would have it, this was not a PR stunt but a choice made by Bob Farquhar to honour his wife, who has a small name plaque on the spacecraft, to be delivered on Saint Valentine's day 2000. Unfortunately, NASA budget for this mission includes operation support for exactly one year.

Thus, will they dare to shut down a fully operational spacecraft on the surface of asteroid Eros, and this on St. Valentine's day?

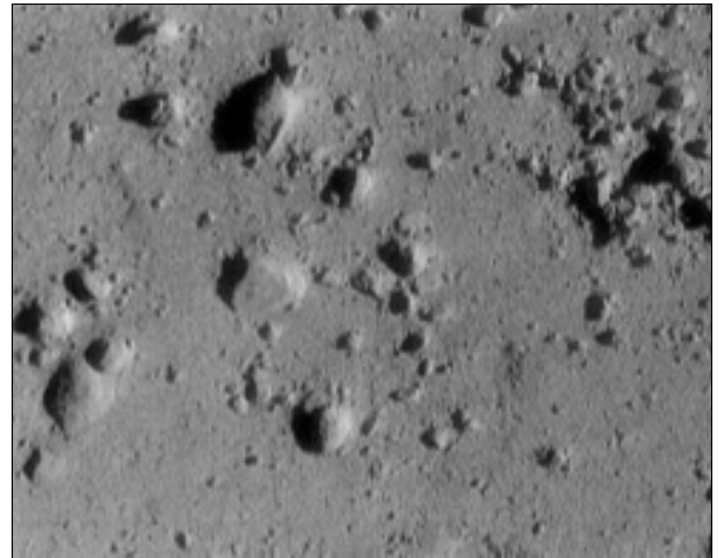
Let's wait and see.



[The location of the landing site](#)

TUMBLINGSTONE REVISITED

We decided to publish the lively account of the descent of the NEAR spacecraft on Eros written by Andrea Milani as a tribute to an outstanding and passionate scientist, who passed away in November 2018. Andrea gave a seminal contribution to practically all the major fields of planetary defence, from creating the very first impact monitoring system to conceiving the asteroid deflection mission concept currently being implemented by the NASA Dart, ASI LICIACube and ESA Hera missions. His deep knowledge of the NEO dynamics also led him to figure out how an innovative wide-field high-sensitivity telescope could bring a major contribution in timely discovering the so-called "imminent impactors". Dubbed "Flyeye" because the multi-faceted optics, the telescope is currently nearing completion by the European Space Agency. Storytelling was also one of Andrea's many interests, one he was particularly proud of, and the Neorockers are glad to have the opportunity to have him back. PS: Andrea's intriguing final question has an answer: NASA did not cut the mission on 2001 Valentine's Day, but operations continued until communications dropped on 28 February.



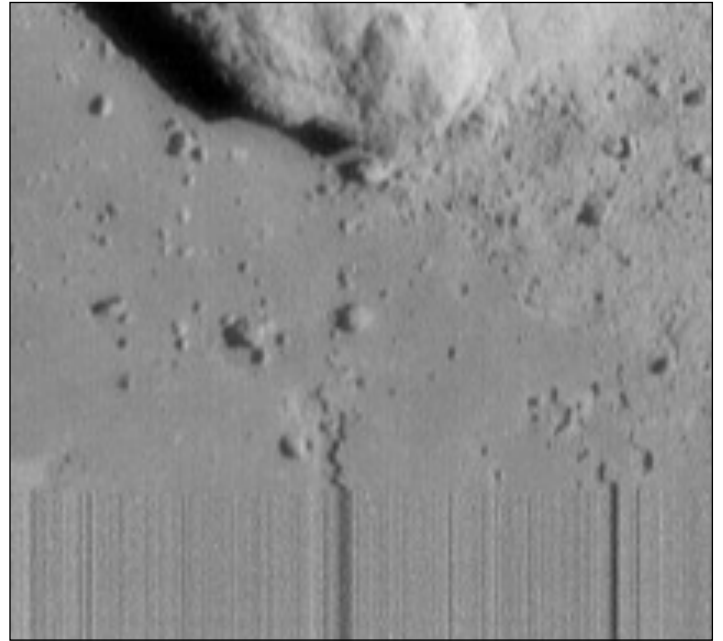
[Images taken during the spacecraft descent on the surface of Eros showing the fine regolith and many sub-meter side boulders](#)



[Valleys and riffs create spectacular landscapes on Eros](#)



[EROS IMAGE ARCHIVE](#)



[The very last image received from Earth: it measures 6 meters across and the streaky lines at the bottom indicate loss of signal as the spacecraft touched down the surface of the asteroid. \(right\)](#)

INTERNATIONAL COORDINATION: FROM AWARENESS TO MITIGATION

Ettore Perozzi
Italian Space Agency, Italy

The NEO risk problem is defined by the actions that must be performed every time a new object is discovered, in order to establish whether it represents an actual threat.

Core activities consist in a loop, where astronomical observations and data processing are performed iteratively until enough information is gathered to assess the risk reliably and, if needed, call for mitigation strategies. Until recently, achieving a good orbital characterisation was the main concern. As such, follow-up observations focused on tracking the object along its path in the sky (astrometry) in order to improve the orbit determination and prediction processes.

In the pioneering years - at the turn of the millennium - a network of professional and amateur astronomers did so through the MPML (Minor Planet Mailing List) internet community. It could rely on the support of the IAU Minor Planet Center (MPC) to submit the outcome of the observational activity and for orbit determination. Two sophisticated software robots (NEODyS at the University of Pisa and Sentry at JPL) performed impact monitoring 100 years ahead in the future, cross checking their results when needed. The Spaceguard Foundation, through the Spaceguard Central Node hosted at INAF, provided the NEO community with tools for optimising the whole process (e.g. prioritisation of follow-up observations).

This scenario is a good example of a community self-coordinating on a voluntary basis and counting on

a worldwide network of assets and competences: from large-aperture telescopes accessed by professional astronomers to private observatories owned by skilled amateurs devoting their time, energy and money to Planetary Defence. This scheme proved successful and reached its climax during the "Aphophis crisis" when, on Christmas time 2004, a 250m object climbed up the risk scales for an impact as early as 2029. The orbit refinement/follow-up loop kept on confirming the possibility of an impact with ever-increasing probabilities. The turning point was finding serendipitous pre-discovery observations of the object, which allowed us to extend the observational arc long enough to improve orbit determination accuracy dramatically and exclude an impact. However, the asteroid will perform an extremely close Earth flyby in 2029.

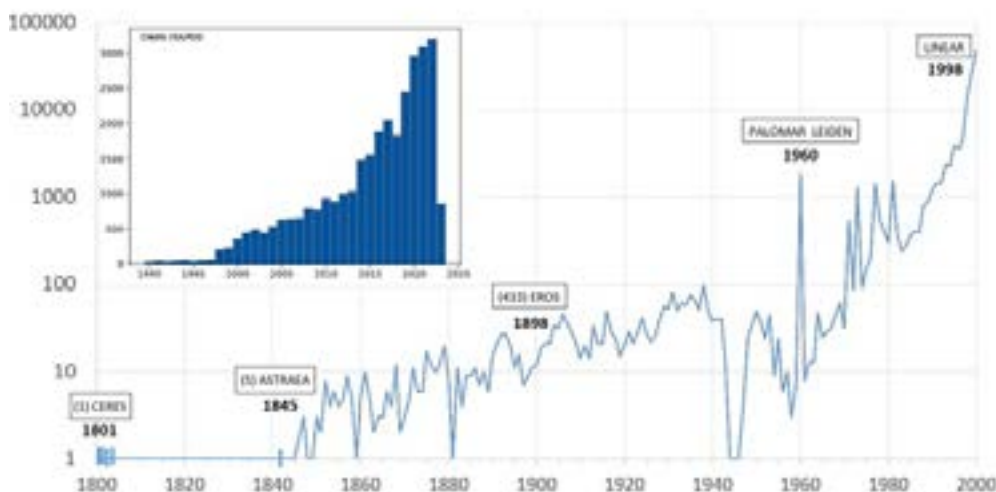
Experience called for a more systemic approach to NEO monitoring and the Chelyabinsk superbolide event in 2013 further strengthened this need. Two major consequences followed: the increasing engagement of NASA, ESA and EU in funding initiatives devoted to NEOs and the operation of new-generation sky surveys (e.g. Pan-STARRS) able to detect objects of increasingly smaller size. This implies not only a sharp increase in the data flux to be processed, but also the need to obtaining information quickly on physical characterisation. For small objects (which are the most likely to hit the Earth) this can be decisive for evaluating the severity of an impact.

The Planetary Society has estimated recently the growth of investments in US planetary defence. It stands at an astounding 4000% in the last 15 years and has led to establishing the NASA Planetary Defence Coordination Office and the JPL Center for NEO Studies (CNEOS). The NEO Surveyor mission will complement the US ground-based surveys, which are presently responsible for more than 90% of the discoveries. At European level, the ESA NEO Coordination Centre has reached full independence in computing its own NEO orbital catalogue and in performing impact monitoring under the ESA Space Safety Programme. Meanwhile, the so-called “Flyeye Telescope” will soon focus in timely detection of the imminent impactors. The EU has included SSA in its 2021-27 Space Programme and has reached an agreement with ESA to manage technical NEO activities.

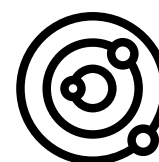
In order to keep pace, international coordination has also progressed. A major concern at the first

Planetary Defence Conference, back in 2009, was the lack of proper governmental interfaces. Today, the IAWN (International Asteroid Warning Network) and SMPAG (Space Mission Planning Advisory Group) committees provide technical support to UNOOSA, the United Nation Office of Outer Space Affairs, which is recognised as the reference institutional body for coordinating actions in case a hazard comes true.

The feeling is that a transition from a science-driven coordination to a planetary defence operational system, providing civil protection alert services similar to those already in place to protect citizens from natural disasters such as earthquakes and floods, is on the run. If this is so, then fostering physical characterisation and providing rapid response physical properties follow-up observations, which have been at the core of the NEOROCKS project, represent key issues for the future.



The long-term (1800-2000) asteroid discovery rate (logarithmic scale)



Note the almost 40-year time span separating the discovery of the four largest asteroids from the next ones and the peaks due to the operation of extended sky surveys (e.g. Palomar-Leiden in 1960, LINEAR in 1998). The year of discovery of the first Near-Earth Asteroid is

also remarked, while the upper left diagram shows the sharp increase of NEO discoveries in the last decades. The lack of data in the years 1945-46 is due to post 2nd world war moving the MPC from Germany to the USA.

MEET THE NEOROCKERS - SAP E SAB

SCIENTIFIC ADVISORY PANEL AND SECURITY ADVISORY BOARD

In our first issue, we introduced you to the partners that make up the NEOROCKS consortium, the core-Neorockers! But they don't work alone. NEOROCKS includes two Advisory Boards, with different and very important roles. In this issue, we are happy to introduce you to their expert members.

The Scientific Advisory Panel (SAP) is an external group, composed of prominent exponents of the international NEO community.

The panel supervises project activities, giving their expert advice on the work flow and on possible improvements. Their help and advice is also instrumental in disseminating project findings and recommendations in international forums.

FEDERICA SPOTO

Federica Spoto is a research scientist at the Minor Planet Centre for the Center for Astrophysics, Harvard & Smithsonian. Federica received her Masters (2010) and PhD (2015) in mathematics from the University of Pisa. Her research focuses on asteroid dynamics and chaotic orbit determination. She is a member of the Data Processing and Analysis Consortium (DPAC) of the ESA Gaia mission, where she is in charge of validation of Solar System observations. We asked Federica about NEOROCKS and why she agreed to be on our Scientific Advisory Panel. This is what she said:

"The NEOROCKS project is a critical piece in the puzzle of understanding and characterizing Near Earth Objects (NEOs) that could impact the Earth soon after their discovery. Being part of this international collaboration is very exciting. The more I work in asteroid dynamics, the more I understand the importance of physical characterization of possible impactors, which is one of the main goal of this project. I'm sure that NEOROCKS is going to have a huge impact in quantifying the hazards of NEOs."

Our Security Advisory Board (SAB) reviews project deliverables, assesses whether they include any security sensitive information and propose measures for preventing the misuse of information.

Let's meet some of them and see what they have to say about NEOROCKS.

"It is a pleasure and honour to serve in the Security Advisory Board on this fundamental topic, which I discovered 20+ years ago, and followed with deep interest ever since, promoting numerous studies on future missions aimed at deflecting Potentially Hazardous Asteroids. NEOROCKS is undoubtedly a key program in this frame."



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN



Robert Jedicke, University of Hawaii Institute for Astronomy

ROBERT JEDICKE

Robert Jedicke is an astronomer at the Institute for Astronomy of the University of Hawai'i. His research involves studies of the populations of asteroids and comets in and beyond our solar system. He is a specialist in Solar System Bodies, with particular expertise in orbit and size distributions of asteroid populations including main belt and near Earth objects, Centaurs, Trans-Neptunian objects, comets, and interstellar objects.

When asked about NEOROCKS, Robert said:

"I am excited to be an international collaborator with the NEOROCKS team members. Their work is critical to understanding the science and quantifying the hazards of Near Earth Objects, and it is important that we maintain communication between European and U.S. groups to ensure rapid and accurate dissemination of information in both directions."

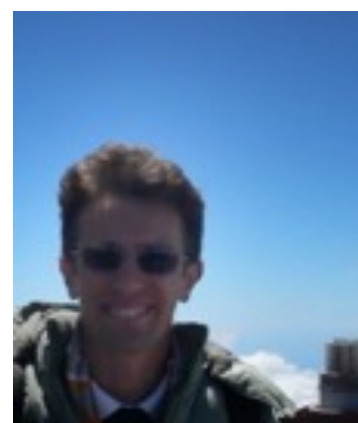


MARCO MICHELI - ESA NEOCC

Marco Micheli is an Astronomer and NEO Observer currently working at the ESA NEO Coordination Centre, ESA's centre dedicated to observing near-Earth asteroids and computing their orbits and probabilities of Earth impact. Marco is specialised in discovery, astrometry and follow-up of NEO and other small Solar System bodies. He is in charge of the coordination and execution of asteroid observations at ESA NEO, while also supporting the Centre's operations and its communication and educational activities.

Marco's response to our question about NEOROCKS was:

"The NEOROCKS project, and its extensive scientific output, has a very close connection to my interests and my work. In particular, its focus on characterisation provides the ideal complement to the astrometric and dynamical observations that are the main subject of my daily activities."



ALESSANDRO ROSSI



Alessandro Rossi is a researcher of the IFAC-CNR Institute. He works in the field of astrodynamics and space debris and is an expert in modelling of the long term evolution of space debris and mitigation strategies, impact risk assessment, optical observation and orbit determination of space objects. He is a member of the ESA SSA Advisory Board and of Task Group NATO SCI-229 TG "Space Environment Support to NATO Space Situational Awareness".

We asked Alessandro what areas of security he deals with, on the SAB of our NEOROCKS project.

"Given the continuously increasing number of launches and of satellites in Earth orbit, Space Surveillance is becoming more and more important. The European SST network of sensors and its related services are now operational. It is important to scrutinise the NEOROCKS observations accurately to avoid any possible breach of sensible data on spacecrafts, mixed within the important scientific results on Near Earth Objects provided by the project."



CHRISTOPHE BONNAL

Christophe Bonnal, Centre National d'Etudes Spatiales, has been involved in Space Debris activities since 1987. He chairs the IAF Space Traffic Management Committee, the IAA Space Debris Committee and coordinates the IAA Space Debris Symposium at IAC. Christophe is French delegate to IADC, ECSS, ISO, and editor of the IAA Space Reports in the field of Space Debris. He is a full member of IAA and member of the IAF IPC Steering Committee.

We asked Christophe for his thoughts about the link between his work and the research being carried out in NEOROCKS.

"It is a pleasure and honour to serve in the Security Advisory Board on this fundamental topic, which I discovered 20+ years ago, and followed with deep interest ever since, promoting numerous studies on future missions aimed at deflecting Potentially Hazardous Asteroids. NEOROCKS is undoubtedly a key program in this frame."



NEOROCKS4KIDS THREE THINGS WE LEARNED

Jessica Huntingford and Sara Banchi, Resolvo Srl, Italy
Ettore Perozzi, Italian Space Agency, Italy

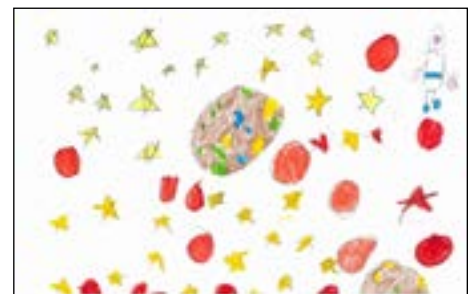
In our NEOROCKS project we have given you LOOOTTSSS of information about asteroids...Do you remember Sara (ya-ya), Julia and Ettore that told you about [how asteroids are formed, where they live, how we can see them and what their names are?](#) And do you remember after that, when our Neorockers [answered all your questions in our mini-newsletter?](#) Now, we are at the end of our project and we want to leave you with some final pieces of knowledge about asteroids that we discovered with Neorocks. We asked Ettore to tell us three important results that our Mini-Neorockers should know. This is what he said.

1 - WE LEARNED THAT ASTEROIDS ARE COLOURED

If you look at a picture of an asteroid, it seems all grey, but this is not the case. In fact, they are coloured. This doesn't mean that one asteroid is bright green, another is scarlet red or electric blue. We are not talking about your football team's kit or your coloured building blocks! It means that they are each made up of different shades of colours. Why is it important? These colours help us to understand what asteroids are made of, without even touching them! We found this out thanks to the international group of Neorockers that observed the asteroids and put their knowledge together.



Anna Giulia



Elina



Maele



Simone E.

2 - WE LEARNED THAT WE CAN CHASE ASTEROIDS

Those asteroids can run, but they can't hide! Our rapid response experiment showed us that when an asteroid passes nearby (remember, "nearby" doesn't mean right by your house. It means one of our Near Earth Objects that is a bit nearer to Earth than the others), we can chase it with our telescopes, even if it goes very fast. How? We can point the Neorockers' powerful telescopes across the world at the right part of the sky in just a few days (which is rapid in the asteroid world!). This way, we can see very quickly where the asteroid is going and what it is made of. This is an important part of the international effort to watch asteroids, just in case their trajectory turns out to be way toooooo close to Earth.



Alessandra



Francesco De

3 - WE LEARNED THAT ASTEROIDS HAVE OLD FAMILY PHOTO ALBUMS

In Observatories around the world, there are loads of photos taken to look at a galaxy or at a star...and nobody noticed that a small asteroid was there too. Through a telescope, an asteroid looks like a tiny dot. With our data mining activities, we went searching for them in archives in many different countries. Why? Because every time you look at an old photo, you see something new. You know when your granny gets out the old photo album and your uncle Alan is in the background of one of the photos, but you don't recognise him because he looks so young?

That's what we did with these astronomical photos: we went back to look at them again, just in case we could find any new pieces of asteroidy information to help with our Planetary Defence.

Mini-Neorockers, thanks for having joined us on this journey! We hope that you have learned lots, that you have had fun with us. Who knows, maybe one day you will become an astrophysicist...and have an asteroid named after you!

Keep on neo-rocking!



Anna I.



Aurora



Emma

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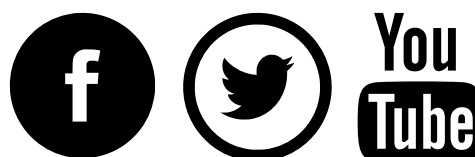
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