DEEPENING ASTEROID DYNAMICS IN THE NEW ERA OF OBSERVATIONS: THE PROJECT MONASTER (MONITORING ASTEROIDS)

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ABSTRACT

Studying the long term orbital evolution of a small body is a quite difficult task because of multiple planetary encounters and non-gravitational forces. However, the precise computation and propagation of an asteroid orbit is essential, not only for scientific purpose, but also for planetary defense. Here we present the Italian project MONASTER (MONitoring ASTERoids) dealing with asteroid dynamics and impacts predictions. The project, established thanks to Italian Space Agency funding, started December 5th, 2022 and it will last three years; it aims to develop innovative mathematical models and algorithms to face the new era of observations and discoveries of minor planets. This paper will briefly describe the structure of the project and a research work that perfectly fits the spirit of the MONASTER project (dealing with tools for imminent impactors) will be shown and discussed.

Keywords: asteorid dynamics; orbit determination; impact monitoring; OrbFit.

1. INTRODUCTION

Since its formation (over 4.5 billion years ago), our planet has been hit many times by natural objects that have orbits in the inner solar system. These objects are generally called Near Earth Objects (NEOs): most of them are Near Earth Asteroids (NEAs), probable fragments of Main Belt Asteroids (MBAs) which, after collisional events and resonances mechanisms, have changed their orbit until reaching one that crosses that of the Earth. The attention for NEOs, and more generally for all the minor bodies of the solar system, grew thanks to the Apollo lunar program of the '60s and '70s of the twentieth century, when the scientific community agreed in stating that the lunar craters are the result of impacts. It is now generally accepted that NEOs pose a potential threat to human civilization. For this reason, our ability to assess the risk of an asteroid or comet colliding with Earth has greatly increased in the last thirty years: not only with algorithmic and computational tools, but also with space missions like DART ([1]) that successfully impacted on Dimorphos (moon of Didymos) last September and Hera ([2]) that will be launched in 2024 to study the Didymos system.

The Celestial Mechanics Group (CMG) of the Department of Mathematics of the University of Pisa has a recognized international experience in the field of Asteroid Dynamics (AD), Orbit Determination (OD) and Impact Monitoring (IM) of NEOs. The IM algorithms were born in Pisa at the end of the '90s thanks to the work of Prof. Andrea Milani Comparetti and his collaborators. At the same time, the Asteroid - Dynamic Site (AstDyS) and NEO Dynamic Site (NEODyS) web services [1] were developed, and, since then, they have been a point of reference for the scientific community dealing with small bodies in the solar system. AstDyS provides data on numbered and multi-opposition MBAs, including orbital elements, their uncertainty, proper elements and ephemerides with uncertainty. NEODyS is instead responsible for collecting the data of the NEOs, computing their orbits, generating ephemerides and estimating the impact risk. The computational engine of AstDyS and NEODyS is the OrbFit software [2], developed by the CMG and various collaborators since the '80s. In the last two years, the NEODyS services and part of those of AstDyS have migrated, thanks to the contribution of the university spin-off company Space Dynamics Services (SpaceDyS[3]), to the ESA NEO Coordination Center (NEOCC), which provides them through its website neo.ssa.esa.int. However, with the completion of the migration of services to ESA, the need was felt to build a joint ASI-CMG research center of excellence about minor bodies based on the legacy of over thirty years of studies in the field by the CMG. The project MONASTER (MONitoring ASTERoids) represents the first step in this direction: aside from deepening the knowledge on AD and OD, we would like to train a new generation of scientists capable of maintaining a Eu-

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[1] newton.spacedys.com/neodys/ ; newton.spacedys.com/astdys2/

[2] adams.dm.unipi.it/orbfit, currently at version 5.0.7

[3] www.spacedys.com

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ropean leadership in this field. In the coming years we will see an increase in the quantity of available observational data, thanks to new terrestrial telescopes ([3], [4]) and the full functioning of space telescopes. To optimally exploit the available data, it is therefore necessary to conceive new mathematical methods and develop algorithms that keep pace with the evolution of hardware (both the observation tools for small bodies and the computation processors).

The paper is organized as follows. Section 2 describes the project structure and the activities that will be carried on during the three years. Section 3 deals with an example, about imminent impactors, of what the project could produce.

2. ACTIVITIES

The activities of the project concern the study of the dynamics of small bodies in the solar system. In particular, the goal is to develop new methods of OD, new algorithms for orbit propagation ([5]) and for IM ([6], [7]); moreover, we want to give space to the dynamics of the MBAs, to the computation of the proper elements ([8]) and to the problem of determining the asteroid families ([9]). All this research will be conducted using the OrbFit software, which will be updated accordingly, and data from the NEODyS and AstDyS web services.

For ease of management, 5 Work Packages (WPs) have been defined (see Fig. 1), which however will not be treated independently; it is clear, for example, that the WP dealing with NEO and IM cannot ignore the results of the WPs working on OD and propagation. Just as it is possible that OD algorithms are specifically designed for a class of objects such as NEOs.

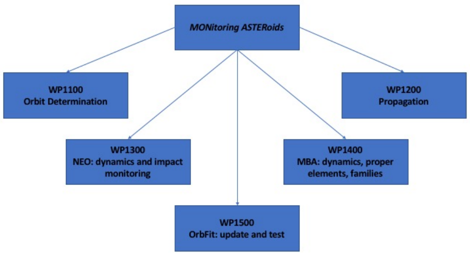

Figure 1. *Work Breakdown Structure (WBS) of the project MONASTER.*

Some of the scientific results of MONASTER would like to move in the direction of improving the pipeline described in Fig. 2, introduced in [10]: recognition of the type of object (NEO, MBA, TNO, IO) starting from the astrometric data present in the NEO Confirmation Page (NEOCP) of the Minor Planet Center (MPC) or in other observational databases, application of the best strategy for managing uncertainty and, in the case of NEOs, selection of the most appropriate algorithm for IM and probability computation.

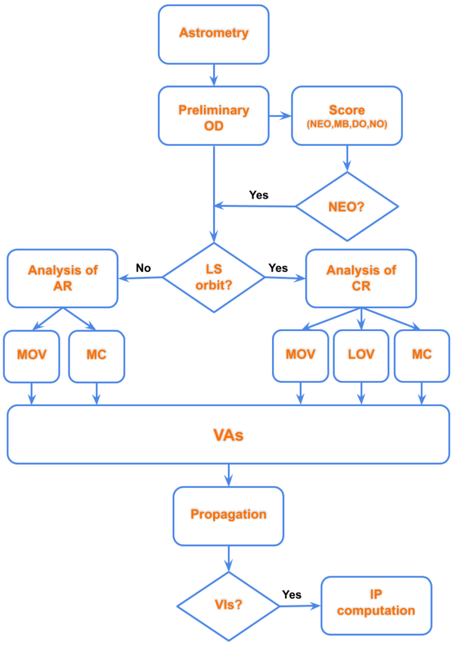

Figure 2. *Preliminary OD allows to compute an orbit starting from a few observations and to classify the object, i.e. whether it is a NEO, a MBA, a Trans Neptunian Object (TNO). As new observations arrive, the aim is to obtain a Least Squares (LS) orbit and analyze the region of uncertainty, called the Confidence Region (CR); such analysis can be conducted using a geometric object, like the Line Of Variations (LOV, [11]), the Manifold Of Variations (MOV, [12]) or appropriate Monte Carlo (MC) methods. If a LS orbit is not reached, it is possible to explore the Admissible Region (AR, [13]) with the MOV or with MC methods. The analysis of the CR and the AR leads to the generation of a swarm of Virtual Asteroids (VAs), orbits compatible with the observations at different levels of confidence, which propagated can be used for orbit identification or to understand if they represent a potential risk for the Earth (Virtual Impactors, VIs).*

2.1. WP1100 Orbit Determination

Once the astrometric data of a single object has been acquired, the first step is to calculate a preliminary orbit and, when possible, a LS orbit. The improvement and diversification (think of space observatories, GAIA data in particular, or the new ground-based telescopes, Fly-Eye, LSST) of observational instruments necessarily leads to the search for new methods of preliminary OD, identification and management of uncertainty.

The WP1100 includes the tasks described below.

- Review of existing literature on OD methods and management of uncertainty; review of observational databases and accuracies.
- Development of new methods of preliminary OD that take into account the observer performance.

- Development of new identification algorithms for large tracklet databases.
- Development of new techniques for managing uncertainty in OD.
- Development of new astrometric error models.

2.2. WP1200 Propagation

A fundamental activity for making accurate predictions is the propagation of orbits. In the case of NEOs, the main criticality lies in close encounters which must necessarily be treated with specific methods.

The WP1200 includes the tasks described below.

- Analysis of the existing literature on regularization methods and algorithms for integrating the small body equations of motions.
- Comparison between the OrbFit propagator and other orbital propagators, especially the CEOD software[4], developed by SpaceDyS. In such software the close encounters of asteroids are managed by combining an exchange of the primary attraction body with a regularized formulation of the two-body problem known as the Kustaanheimo-Stiefel regularization. The Orbfit software does not change the primary and adopts the classic Cartesian representation of the state using different numerical integrators. In order to improve the performance of OrbFit, we plan to carry out a large comparison in terms of accuracy in determining the orbits of asteroids undergoing close planetary encounters.
- Development of new methods and strategies for orbit propagation.

2.3. WP1300 NEO: dynamics and IM

The main activity of this WP is certainly represented by IM, consisting in the research and characterization of the VIs of each object; it will be carried out both for ordinary objects (possible impact between 1 and 100 years after discovery) and for the so-called *imminent impactors* ([14]).

The WP1300 includes the tasks described below.

- Analysis of existing literature on NEO dynamics and IM.
- IM in the ordinary case (1-100 years): this will not be a routine activity, but it will be crucial in order to compare with the new algorithms implemented and to face any critical cases highlighted by the astronomical community.
- Computation, according to the type of orbit and associated uncertainty, of the horizon of impact prediction. This activity is strictly related to the definition of *scattering encounter* ([15]).
- Long-term impact monitoring (100-200 years and more) with the determination of non-gravitational effects like the Yarkovsky one ([16]).
- Monitoring of imminent impactors and interaction with the management of surveys for the discovery of asteroids.

2.4. WP1400 MBA: dynamics, proper elements, families

MBAs have very interesting dynamics that can provide us important information on the formation of the solar system.

The WP1400 includes the tasks described below.

- Analysis of the existing literature on the computation of the MBA elements, on the definition of families and on the estimation of ages.
- Improvement of the computations of the secular resonances in the Main Belt: in particular, we want to understand how serious is, and possibly solve, the problem of the cycle slips that appear in the filtering procedure and which affect the accuracy of the determination of the positions of the secular resonances in the phase space of the proper elements of the asteroid. Furthermore, we want to investigate the extent of the perturbative effects of some secular resonances (e.g. g - g_5), which are still largely unclear. A better understanding of the location of these resonances is essential to discover their role in the long-term dynamics of MBAs.
- Characterization of the positions of the secular resonances of the MBAs up to degree six in eccentricity and inclination with Jupiter and Saturn and possibly with other planets. Starting from Le Verrier's development of the perturbing function and from the application of transformations similar to those used by Yuasa (1973, [17]) we want to set the problem with respect to an invariable plane.
- Update of the proper elements computation and development of new methods for age estimation.

2.5. WP1500 OrbFit: update and test

As already mentioned, the OrbFit software has been developed by CMG and various collaborators since the '80s. In addition to being the computational engine of the AstDyS and NEODyS web services, it is used by the scientific and astronomical community and has also become the reference software of the Minor Planet Center

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[4] www.ceodproject.it

(MPC). OrbFit consists of two parts: a public one, distributed under the GPL license and downloadable from the site, and one dedicated to research needs. OrbFit will be the tool to test the new algorithms developed in the previous WPs and will be updated accordingly. A switch from a heliocentric to a barycentric propagator will be investigated.

3. TOOL FOR IMMINENT IMPACTORS

In this section we present an example of what the project could produce; in particular, we will show how to use the AR and the Minumum Orbit Intersection Distance (MOID) concepts to ease the astronomers in handling few observations of potential impactors. The tool is exhaustively explained in [18].

3.1. Analysis of the MOID = 0 curve in the AR

When the observational resources are scarce, the only thing to do is computing an attributable (a four dimensional vector built by polynomial interpolation which synthesizes the astrometric data) and the MOV. After the computation of the MOV, by sampling the AR with a grid or a cobweb, the idea is to loop over the resulting MOV points, computing and assigning to each couple $(\rho, \dot{\rho})$ the respective value of the MOID and its covariance ([19]). The MOID computation is done by searching for the minimum points of the Keplerian distance function according to an algebraic method described in [20].

The MOV points are then represented on the AR, according to the following colour-code:

- green dots have MOID > 0.05 AU, thus representing non-hazardous orbits;
- yellow dots have 5×10^{-5} AU $<$ MOID ≤ 0.05 AU, thus representing the orbits for which the object, if big enough, is to be considered a Potentially Hazardous Asteroid (PHA);
- red dots correspond to 5×10^{-7} AU $<$ MOID $\leq$ 5×10^{-5} AU, where the upper threshold is of the order of the Earth radius;
- black dots correspond to MOID $\leq 5 \times 10^{-7}$ AU; we consider these points compatible with MOID=0 and observe that, when present, their disposition on the range-range rate plane follows a curved line;
- a black cross highlights the LS orbit (if available).

All representations of the AR that appear in this work also show the following lines.

- Red line: outer boundary of the AR, outside of which the object would not belong to the solar system;
- Green line: inner boundary of the AR, left of which the object would be a satellite of the Earth;
- Magenta solid lines: lines corresponding to thresholds in absolute magnitude H;
- Magenta dashed line: shooting star limit, i.e., the line left of which the absolute magnitude is $H > 34.5$, corresponding to a small object that would completely disintegrate into the atmosphere.

When performed, a fit of the MOID$= 0$ curve with a degree 2 polynomial was represented as a black solid line.

3.2. Test Cases: past impactors

We ran tests over data collected for various objects (past impactors, lost asteroids and NEOCP objects), but here we present the results for past impactors, objects that have been discovered before their impact with the Earth. We tested our tool over four objects.

- 2008TC$_3$: discovered 19 h before impact by the Catalina Sky Survey (CSS) on 7 October 2008, it measured 4.1 metres in diameter. It exploded at an estimated 37 kilometres altitude above the Nubian Desert in Sudan. A tracklet of seven observations was enough to determine an Impact Probability (IP) of 99.7%. Soon after discovery, hundreds of astrometric observations submitted to the MPC allowed for the computation of the impact corridor and the later retrieval of residuals of the meteorite.

  In Fig. 3 we show the output of the tool for tracklets of four and seven observations. We observe that using the first batch of observations, the tool finds a large number of MOV points below the MOID$< 10^{-5}$ threshold, corresponding to a high follow-up priority.

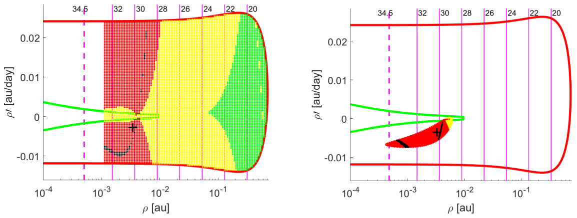

Figure 3. 2008TC$_3$: AR for tracklets of 4 observations (left) and 7 observations (right)

- 2014AA: discovered on New Year's Eve, 21 h before impact, this object had very little follow-up (this was mainly due to the peculiar night of its first detection). The resulting delay in recognition of the imminent impact made the necessity of an automated warning system very clear. Still, as demonstrated in [21], the few observations available were sufficient to compute a 100% IP.

In Fig. 4 we show the output of the tool for tracklets of three and seven observations. From the three observations tracklet, we obtained a grid sampling of the AR, showing a large portion of the MOV having MOID$< 10^{-5}$, while the least squares orbit was found on the MOID=0 line. Both these circumstances would have awarded 2014AA a very high priority score. The seven observations tracklet made it possible to compute a reliable nominal solution and, consequently, to sample the MOV with a cobweb. Since the nominal solution still lay on the MOID=0 line, the impact was virtually certain.

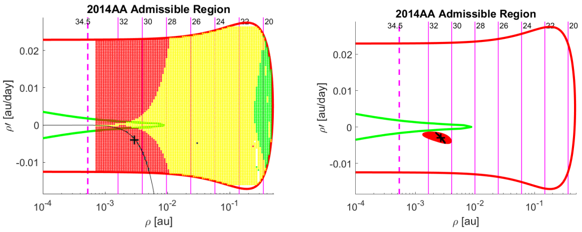

Figure 4. 2014AA: AR for tracklets of 3 observations (left) and 7 observations (right)

- 2018LA: a small Apollo-type NEA discovered by the Mt. Lemmon Survey on 2 June 2018. Only 8 h later, it impacted the Earth's atmosphere over Botswana, becoming the third imminent impactor ever detected and the first opportunity to test Scout[5] and NEOScan[6] (the JPL and Pisa systems for imminent impactors) on a real case. The object could not be detected before it came very close to the Earth due to its high entry velocity and small size (the estimated diameter was of a few metres). In the following hours after the first observational data were published on the NEOCP, follow-up observations were performed and four tracklets were obtained. Results of the four runs of the tool over the tracklets of 3, 11, 12 and 14 observations are shown in Fig. 5 and Fig. 6.

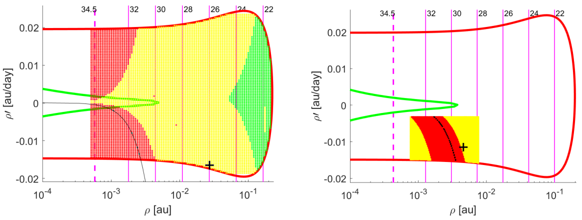

Figure 5. 2018LA: AR of tracklets of 3 observations (left) and 7 observations (right)

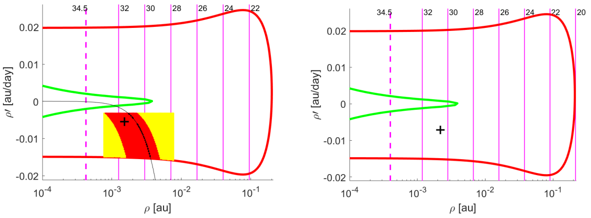

Figure 6. 2018LA: AR of tracklets of 12 observations (left) and 14 observations (right)

- 2019MO: discovered by the Asteroid Terrestrial-impact Last Alert System (ATLAS) Mauna Loa observatory on 22 June 2019 at 9:49 (less than 12 h before impact) this object was a small (4-6 metres in diameter) Apollo-type Near-Earth Asteroid. It was at first registered in the NEOCP with four observations and pointed out as an imminent impactor by NEOScan, but the low score assigned prevented prompt follow-up, so that three additional observations from the Pan-STARRS2 images were recovered only after the impact, a procedure known as *precovery*. In Fig. 7 we show the output of the tool for the first tracklet of four observations and for the seven observations precovered tracklet. Post-impact computations revealed that earlier availability of the seven observations tracklet would have yielded $IP = 99.8\%$, thus resulting in a high priority score.

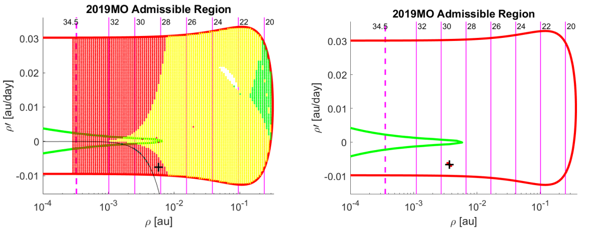

Figure 7. 2019MO: AR of tracklets of 4 observations (left) and 7 observations (right)

Seeing how the four past impactors behaved, we state that to determine if an object poses an imminent threat, the $\text{MOID} = 0$ line has a relevant predictive value. To back up this statement we take two objects for which the nominal solution did not lie exactly on the line, (i.e., 2018LA and 2019MO) and show that even in these cases it provides useful information.

For 2018LA, we performed a second degree polynomial fit to the MOID = 0 points obtained from the 12 observations tracklet, finding the following fit parameters:

$$p_1 = (-1253 \pm 71)$$

$$p_2 = (2.970 \pm 3.834) \times 10^{-1}$$

$$p_3 = (1.365 \times 10^{-5} \pm 5.0105 \times 10^{-4}).$$

Even if the reliable nominal solution found from the 14 observations tracklet does not belong to the MOID=0 line, we can see that it falls inside the uncertainty range

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[5] cneos.jpl.nasa.gov/scout

[6] newton.spacedys.com/neodys/NEOScan

of the fit, as shown in Fig. 8, where the blue solid lines have been drawn by assigning to the fit polynomial the maximal and minimal values of the parameters allowed by their uncertainty.

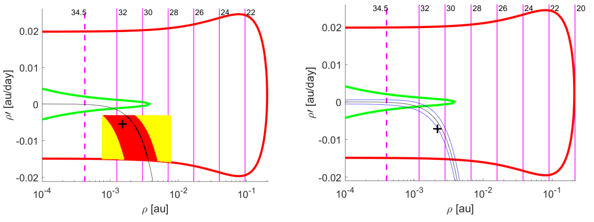

Figure 8. Fit (black curve) and uncertainty (blue curves) of the MOID = 0 line for 2018LA.

The same procedure has been repeated for 2019MO, obtaining the following fit parameters from the four observations tracklet:

$$p_1 = (-492 \pm 61)$$

$$p_2 = (3.773 \pm 3.542) \times 10^{-1}$$

$$p_3 = (1.031 \pm 4.943) \times 10^{-4}.$$

and drawing the corresponding curves on the AR obtained from the seven observations tracklet. The reliable nominal solution and cobweb fall inside the fit uncertainty region, as shown in Fig. 9.

For three out of the four past impactors, the line has substantially the same shape. This suggests the possibility of finding a common expression that would enable us to draw the line a priori on the AR of a generic NEO and search for its intersections with the MOV. This would require an analytical treatment, that will be studied during the three years of the project MONASTER.

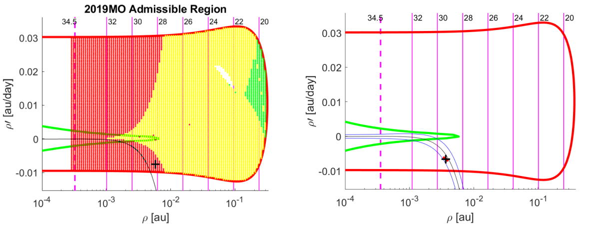

Figure 9. Fit (black curve) and uncertainty (blue curves) of the MOID = 0 line for 2019MO.

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