Impact Earth! Protecting the UK and Further Afield from Impacts by Near Earth Objects.

Royal Astronomical Society meeting, London

Friday May 12th, 2023.

Hybrid Programme

Organisers: Prof. Mark Burchell (Univ. Kent, m.j.burchell@kent.ac.uk), Prof. Gareth Collins (Imperial College), Prof. Massimiliano Vasile (Univ. Strathclyde).

Location: The RAS, Burlington House. Attendance in person is welcome. Those who register in advance via the RAS website for online attendance, will receive a zoom link on the morning of the meeting.

Programme

Doors open 10 am.

10:20 Welcome (Mark Burchell). Email: m.j.burchell@kent.ac.uk

Start of am session (Chair GC) at 10:25 am

Setting the Scene

10:25 (5 min talk) Introduction: The Challenges (An Overview). Mark Burchell, Univ. of Kent. m.j.burchell@kent.ac.uk **CONFIRMED in person**

10:30 (10 min talk + 3 min Q&A) The risk of asteroid impact to the UK: how worried should we be? Gareth Collins, Imperial College. g.collins@imperial.ac.uk **CONFIRMED in person**

What is out there?

10:43 (10 min talk + 3 min Q&A) Robert Siverd, Near-Earth Asteroid Detection with the ATLAS Survey. Univ. Hawaii. rsiverd@hawaii.edu **CONFIRMED online**

10:56 (10 min talk + 3 min Q&A) Cian McDonnell, NEOMIR or not NEOMIR? A feasibility study of an alternative to ESA's NEOMIR. Cranfield Univ. Email: Ambre.Autrive.878@cranfield.ac.uk **CONFIRMED in person**

11:09 (10 min talk + 3 min Q&A) Marta Ceccaroni, Defending Earth from Asteroid Hazard: how UK can play a central role. Cranfield Univ. Email: m.ceccaroni@cranfield.ac.uk **CONFIRMED online**

11:22 (10 min talk + 3 min Q&A) Megan Schwamb, Earth Impactors in the Era of Rubin Observatory. Queen's University Belfast. Email: m.schwamb@qub.ac.uk **CONFIRMED in person**

11:35 (10 min talk + 3 min Q&A) Giovanni Gronchi, On the minimum orbit intersection distance (MOID) between a near-Earth asteroid and the Earth. *Dipartimento di Matematica, Università di Pisa, Italy.* Email: giovanni.federico.gronchi@unipi.it **CONFIRMED Online**

DART/HERA

11:48 Guest speaker (20 min talk + 5 min Q&A) Sabina Raducan. First results from the DART impact on asteroid Dimorphos. Univ. Bern, Switzerland. Email sabina.raducan@unibe.ch **CONFIRMED**

12:13 (10 min talk + 3 min Q&A) Brian Murphy, DART Ejecta Evolution using VLT/MUSE. Edinburgh Univ. Email: brian.murphy@ed.ac.uk **CONFIRMED in person**

12:26 (10 min talk + 3 min Q&A) Agata Rożek, The orbital period change of asteroid Dimorphos as a result of DART mission impact. Edinburgh Univ. Email: Email: a.rozek@ed.ac.uk **CONFIRMED in person**

12:39 (10 min talk + 3 min Q&A) Aurelio Kaluthantrige, Autonomous navigation around Didymos using CNN-based Image Processing. Univ. Strathclyde. Email: mewantha.kaluthantrige-don@strath.ac.uk **CONFIRMED online**

12:52 (10 min talk + 3 min Q&A) Alan Fitzsimmons, The ESA Hera Mission: Completing the Experiment. Queens University Belfast. Email: a.fitzsimmons@qub.ac.uk **CONFIRMED online**

Close am session 1:05 pm

Lunch 1:05 pm – 2 pm. During lunch there will be an extra 15 min presentation on visualisation of impact simulations by Jacob Kegerreis (who will also be speaking in the afternoon session). **CONFIRMED in person**

Lunch time display in library by Matthias van Ginneken (Kent) *Explore micrometeorites with your eyes and, for the first time, with you hands. This exhibit takes full advantage of recent advances in X-ray computed tomography and 3D printing to give the perfect idea of the shape and structure of micrometeorites.* **CONFIRMED in person**

Please will the audience assemble after lunch by 1:55 pm for a prompt 2 pm start

Start of pm session (Chair MV) at 2:00 am

2:00 Guest speaker (20 min talk + 5 min Q&A) The Legal and Policy aspects of Planetary Defence (**online** from USA. Alissa Haddaji, Harvard). Email: alissa.haddaji@spaceconsortium.com **CONFIRMED online**

Regional Threats

2:25 (10 min talk + 2 min Q&A) Ashley King, The UK Fireball Alliance – building an all-sky UK meteor observatory. The Natural History Museum. Email: a.king@nhm.ac.uk **CONFIRMED online**

2:37 (10 min talk + 2 min Q&A) Matthias van Ginneken, Meteoritic event recorded in Antarctic ice – part 2: further exploring the BIT-58 debris layer and its implications for the impact record of Earth. Univ. of Kent. Email: m.van-ginneken@kent.ac.uk **CONFIRMED in person**

2:49 (10 min talk + 2 min Q&A) Mark Boslough, 2023 PDC exercise: Global tsunami from land or ocean impact. Univ. New Mexico. Email: mbeb@unm.edu **CONFIRMED Online**

Living with uncertainty

3:01 (10 min talk + 2 min Q&A) Yirui Wang, Intelligent Decision Support System for NEO Impact Scenarios Identification and Deflection Strategies Selection under Uncertainty. Univ. of Strathclyde. Email: yirui.wang@strath.ac.uk **CONFIRMED online**

3:13 (10 min talk + 2 min Q&A) Marco Fenucci, The risk assessment pillar at ESA's planetary defense office. ESA-NEO Coordination Centre, Italy. Email: Marco.Fenucci@ext.esa.int **CONFIRMED online**

Giant Impacts

3:25 (5 min talk) Sam Halim, Investigating the ejection of low-pressure material from earth to the moon using numerical modelling. Birkbeck College, London. Email: shalim03@mail.bbk.ac.uk **CONFIRMED online**

3:30 (5 min talk) Jacob Kegerreis, Immediate origin of the Moon as a post-impact satellite & Visualisation of Simulations. Durham Univ. Email: jacob.kegerreis@durham.ac.uk **CONFIRMED in person**

3:35: Close session with final remarks and thanks by Massimiliano Vassile (email: massimiliano.vasile@strath.ac.uk)**.**

Abstracts

The Challenges (An Overview)

Mark J. Burchell, Centre for Astrophysics and Planetary Science, Dept. of Physics and Astronomy, Univ. of Kent. Canterbury, Kent CT2 7NH. United Kingdom. (m.j.burchell@kent.ac.uk)

This talk provides a brief introduction to the challenges posed by arrival of extraterrestrial material at the Earth. Even at mm scale, this size provides a threat to spacecraft in Earth Orbit, but can also enter the atmosphere and be decelerated to form a collection of cosmic dust at the Earth's surface. Centimetre to metre-sized objects will burn up on entry producing shooting stars and small meteorites. Larger, 10's of m sized objects cam explode in air bursts, showing material on the ground and producing a shock wave blast over the surrounding terrain. Finally at larger sizes, the arriving material impacts the Earth's surface at high speed (in excess of several km s^{-1}), producing the classic impact crater (if on land) or some form of transient crater in the water of the ocean which then refills and can cause tsunamis. In this meeting, a wide range of these phenomena and the issues they raise (frequency, consequences, etc.) will be considered, along with recent results on efforts to mitigate the risk by diverting the orbit of a small solar system object (the asteroid moonlet Dimorphos).

The risk of asteroid impact to the UK: how worried should we be?

Gareth S. Collins, Imperial College London, UK. Email: g.collins@imperial.ac.uk

Asteroid impacts are one of the most extreme examples of a low probability-high consequence natural hazard. The abrupt demise of the dinosaurs and Hollywood blockbusters have associated impact-induced Armageddon with a 1-in-a-100-million year, city-sized asteroid that devastates the planet, bringing global darkening and freezing temperatures for decades[1]. Thanks to comprehensive astronomical surveys of km-scale asteroids, the chance of such a fate is vanishingly small for the foreseeable future[2]. Instead, modern analysis of the impact hazard emphasises the threat of much smaller, but more frequent collisions that cause damage on a regional scale[3].

Asteroids 20-100 m in diameter disrupt explosively in the atmosphere and close enough to the ground to generate a blast wave that could cause damage over a city-sized region[4]. Slightly larger asteroids strike the surface and can also generate hazardous tsunami waves or plumes of dust and debris[5]. The consequences of such events occurring over or just offshore of a major conurbation would be severe. And as a densely populated island nation, the UK is more vulnerable to these hazards than many other parts of the world. However, while the whereabouts and number of potentially hazardous objects in these categories is not known, which complicates risk assessment, the probability of such an event remains reassuringly small.

The UK's National Risk Register[6] (NRR) is a list of the most significant risks, including some environmental hazards, that could occur in the next two years and that could have a substantial impact on the UK. The purpose of the NRR is to set out what the UK government is doing to respond to these risks; to help emergency planners decide which risks to plan for; and to help make the public aware of and prepare for these risks. Risks included in the NRR range in probability of occurrence from <1 in 500 to >1 in 5 and in consequences from affecting >10,000 people to a significant proportion of the population. The risk of asteroid impact is not on the NRR, but should it be? Does the potential scale of the consequences offset the small probability of occurrence? Would emergency planners benefit from considering the risk? Would the public benefit from greater awareness of the asteroid hazard?

References

1. Morgan, J. V., Bralower, T. J., Brugger, J. & Wünnemann, K. The Chicxulub impact and its environmental consequences. *Nat Rev Earth Environ* **3**, 338–354 (2022).

2. Stokes, G. H. *et al. Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*. 216 https://cneos.jpl.nasa.gov/doc/SDT_report_2017.html (2017).

3. Mathias, D. L., Wheeler, L. F. & Dotson, J. L. A probabilistic asteroid impact risk model: assessment of sub-300 m impacts. *Icarus* **289**, 106–119 (2017).

4. Collins, G. S., Melosh, H. J. & Marcus, R. A. Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. *Meteoritics & Planetary Science* **40**, 817–840 (2005).

5. Chesley, S. R. & Ward, S. N. A Quantitative Assessment of the Human and Economic Hazard from Impact-generated Tsunami. *Nat Hazards* **38**, 355–374 (2006).

6. National Risk Register 2020. *GOV.UK* https://www.gov.uk/government/publications/national-risk-register-2020.

Near-Earth Asteroid Detection with the ATLAS Survey

Robert J. Siverd[1], John Tonry[1], Larry Denneau[1], Alan Fitzsimmons[2], Nicolas Erasmus[3], Stephen Smartt[4,2], Ken Smith[2]

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[3]South African Astronomical Observatory, Cape Town, South Africa

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The Asteroid Terrestrial-impact Last Alert System (ATLAS) is a NASA-funded, all-sky, robotic telescope survey developed by the University of Hawaii to efficiently detect hazardous near-Earth asteroids (NEAs) and other moving objects. Operated by the University of Hawaii in conjunction with collaborators in the UK and elsewhere around the world, ATLAS employs four wide-field telescopes to survey the entire visible night sky to a limiting dark-time V magnitude of 19.7 with a cadence of roughly two days. Two of the ATLAS telescopes, located in Hawaii, have been in operation since 2017. Two additional units have been operational in Chile and South Africa since 2022. A fifth unit, currently under construction in the Canary Islands, will join the ATLAS survey in the near future. In this presentation I will provide a brief overview of the current ATLAS survey system, its asteroid detection ability, and the ongoing effort to optimize our system for the newly added telescopes.

NEOMIR or not NEOMIR? A feasibility study of an alternative to ESA's NEOMIR

A., Autrive, S., Alotaibi, M., Ben Amara, G., Bhalerao, R., Bussemey, H., Cankiran, D., Divakaran, H., Garny, **C., McDonnell**, S., Motais de Narbonne, J., Natier, M., Renault, U., Roy Chowdhury, N., Stephen, M., Ceccaroni.

Cranfield University

One of the major steps in planning planetary defense missions is to identify the Near-Earth Objects (NEO) that represent a threat to Earth, especially imminent impactors. The asteroids approaching the Earth from the direction away from the Sun can easily be detected using ground-based telescopes, but what about those coming from the Sun's direction? Only space-based telescopes observing in the infrared can detect them without being blinded by the Sun.

NEOMIR (Near Earth Object Mission in the InfraRed) is an ESA mission aiming to put such a telescope into a halo orbit around the Sun-Earth Lagrange point L1, in order to detect asteroids coming from the direction of the Sun and with a diameter larger than 40 m. In this study, the preliminary design of NEOMIR was examined and then compared with an alternative mission design using a Distant Retrograde Orbit (DRO) around the Earth instead of the halo orbit. A preliminary feasibility study was thus undertaken, providing a novel spacecraft design and transfer strategy, and a comparison between both scenarios, based on cost, efficiency, detection rate, and warning time. The DRO mission here proposed provides the main advantage of a substantially increased warning time (i.e., time between the detection of an asteroid and its potential impact with Earth) while decreasing the required size of the optics. This solution also provides better detection rates while increasing reliability in case of failure. Because of the nature of DROs, however, these advantages come with an increased budget and overall complexity of the mission, as the alternative mission requires 4 identical spacecraft launched using two Ariane 64, thus increasing the cost of the mission. If this solution is implemented in the future, it would become the first mission to ever put a satellite in a Distant Retrograde Orbit in the Sun-Earth system.

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Defending Earth from Asteroid Hazard: how UK can play a central role.

Dr. Marta Ceccaroni,
m.ceccaroni@cranfield.ac.uk.

ESA's NEO Coordination Centre and NASA's CNEOS are the sole two organisations recognised by the Minor Planet Center (MPC) to perform Orbit Determination (OD) and Impact Monitoring (IM) of Near Earth Objects. These two systems, respectively deriving from Clomon-2 and Sentry, despite some differences in the propagation methods, share the common characteristic of being based on the LOV method. This method is dating back more than 20 years, during which several major improvements have become available, like the increase of reachable computational power and the rise of machine learning. Moreover, as they originated from the same group of researchers, the two organisations exhibit several arrangements like, for example, the way in which observations and observers are weighted and filtered.

The MPC impose a parity system: whenever ESA and NASA's calculations do not agree within a certain threshold, for example, on the impact probability, the two are called to undertake common evaluations and come to a shared conclusion before any result may be published or disclosed. Third parties are cut off from this process and to date no other reliable source of information exist.

In this work, the future role of the United Kingdom in monitoring the Asteroid Hazard is discussed. Indeed, the United Kingdom has the technological capability to become the third recognised institution to defend the Earth from potentially hazardous asteroids, focussing, ad example, on imminent impactors, early stage OD for unconfirmed asteroids and developing more reliable impact-corridor evaluation models.

This can be achieved by exploiting recent advances in mathematics, like short arc orbital determination, and computer science, including but not limited to machine learning techniques and resources available in the open-source community. In this regard, the importance of keeping the OD and IM software open-source is stressed, thus allowing the global community of researchers to develop and advance it, in a fully-transparent way that also prevents the system to remain locked into an ivory tower.

Earth Impactors in the Era of Rubin Observatory

Meg Schwamb (Queen's University Belfast), Colin Orion Chandler (University of Washington), Sarah Greenstreet (University of Washington), and Mario Jurić (University of Washington)

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The Vera C. Rubin Observatory is currently under construction in Chile. This international facility will radically transform our view of the changing night sky. Rubin Observatory will contain an 8.2-m telescope equipped with the world's largest optical imager, a 3.2-gigapixel camera capable of capturing a 10 square degree patch of the night sky (~40 times the size of the full Moon) in a single exposure. Starting in about mid-2025, the Rubin Observatory will carry out the widest and deepest optical survey to date, the Legacy Survey of Space and Time (LSST), scanning the visible sky approximately once every three nights for ten years.

In addition to discovering thousands to hundreds of thousands of explosive transients, LSST will discover and monitor over 5 million Solar System asteroids, comets, interstellar objects, and trans-Neptunian objects. LSST alone is expected to discover approximately ~60% of the potentially Hazardous Asteroids (PHAs) with $H < 22$. In this talk, I will present the potential impactor science opportunities that will be available in the LSST era. I will also provide updates on current and future activities within the LSST Solar System Science Collaboration and highlight avenues for future synergies between the planetary astronomy, planetary defense, and fireball/meteorite communities in the Rubin era.

On the minimum orbit intersection distance (MOID) between a near-Earth asteroid and the Earth

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Keywords: *asteroid hazard, impact monitoring, orbit geometry*

ABSTRACT

The computation of the distance between two Keplerian trajectories A, A' with a common focus, also called MOID (Minimum Orbit Intersection Distance), is useful for different purposes. Small values of the MOID are relevant for the assessment of the hazard of near-Earth asteroids (NEAs) with the Earth. On the other hand, we may wish to check whether the MOID can assume large values, because in this case it is more difficult to observe a small celestial body moving along A from a point following A', and the probability to miss its discovery is higher. Therefore, understanding the occurrence of large values of the MOID is relevant to detect observational biases in the known population of faint NEAs.

We shall discuss some algorithms for the computation of the MOID and the features of the distance between two points on two Keplerian trajectories with a common focus.

This is a joint work with Giulio Baù and Clara Grassi

Guest speaker

First results from the DART impact on asteroid Dimorphos

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Following a 10-month journey through space, NASA's Double Asteroid Redirection Test (DART) spacecraft successfully impacted the asteroid Dimorphos, ~ 160 meters in diameter and the secondary of the Didymos system, at more than 6 km/s. This impact occurred on September 26, 2022 and caused a more than 30-minute shift in Dimorphos' orbit around its primary. The aftermath of the impact has been observed by various means, including Earth-based and space-based telescopes. This experiment marks a crucial milestone towards developing effective strategies for deflecting asteroids, thereby protecting our planet. Our research includes high-fidelity numerical simulations of the impact which help us to determine the asteroid's properties. The European Space Agency's Hera mission is scheduled to launch in October 2024 and will measure the results of the DART mission kinetic impactor test, as well as provide valuable insights for future asteroid deflection efforts.

DART Ejecta Evolution using VLT/MUSE.

B. P. Murphy[1] and C. Opitom[1] and C. Snodgrass[1] and S. Bagnulo[2] and S. F. Green[3] and M. M. Knight[4]and J. de Léon[5,6] and J.-Y. Li[7] and D. Gardener[1]. [1]Institute for Astronomy, Edinburgh University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK (brian.murphy@ed.ac.uk), [2]Armagh Observatory & Planetarium, College Hill, Armagh, BT61 9DG, UK, [3]School of Physical Sciences, The Open University, Milton Keynes MK7 6AA, UK, [4]United States Naval Academy, Annapolis, MD, USA. [5]Instituto de Astrofísica de Canarias (IAC), C/Vía Láctea s/n, E-38205 La Laguna, Spain, [6]Department of Astrophysics, University of La Laguna, Tenerife, Spain, [7]Planetary Science Institute, Tucson, AZ, USA

Abstract: NASA's Planetary Defense Coordination Office commissioned the Double Asteroid Redirection Test (DART) mission to investigate the effectiveness of the kinetic impactor redirect technique, which could mitigate the chances that a future planetary impactor would strike Earth. On 2022 September 26, at 23:14 UT, the DART spacecraft impacted the non-hazardous 151-m diameter asteroid Dimorphos, which orbits the larger 780-m diameter Didymos.[1-2] Ground-based observations from the Multi-Unit Spectrographic Explorer (MUSE) instrument at the Very Large Telescope UT4 (VLT) caught the ensuing ejection cone at remarkable spatial, spectral, and temporal resolutions. These ground-based observations cover T+04 to T+655 hours post-impact and were collected by our team as a part of the ESO proposals 109.2361 and 110.23XL. The observations were taken using the MUSE integral field spectrometer's Narrow Field Mode (NFM, 8''x8'') with adaptive optics and Wide Field Mode (WFM, 60''x60'') without adaptive optics.[3] A total of 35 and 67 centred NFM and WFM exposures were selected for analysis, supplemented by several dozen off-centred exposures to capture the tail. We analyzed the morphological evolution of the ejecta in the 2D WFM and NFM images, specifically tracking the velocity of early clumps (concentration of materials with no resolvable structure) in the ejecta plume. We also extracted position angle measurements of the tail, northern ejecta cone edge, and southern ejecta cone edge. Similarly, we calculated the relative reflectance spectrum normalized at 600 nm for each spaxel in the 3D data cubes, and fitted a first order polynomial to the relative reflectance slope between 500 and 850 nm. We produced colour maps that contained each spaxel's slope value for each exposure, and co-added the colour maps to also increase the signal-to-noise for all of our nights.[4] Initial estimates of averaged clump velocities on 27 Sep are $\underline{\square} = 13.7 \pm 2$ m/s, which is consistent with ejection at time of DART impact (see Fig. 1). Position angles extracted from rho-theta projections of the 2D images throughout the duration of our observations suggest a slightly curved tail, which compliments similar measurements by the Hubble Space Telescope.[5] The relative reflectance spectrum colour maps show that the initial ejecta is bluer, and that the later tail, northern, and southern ejecta cone edges are redder. This could imply that the initial ejecta is comprised of smaller particulate, while the later ejecta is larger. Possible drivers of this phenomena could be that smaller particles were ejecta from the system at higher speeds, therefore representing the majority of initial ejecta in the early images. Larger particles were ejected from the system at slower speeds, and remained in the field of view over longer timescales. Similarly, the tail is observed to become redder over time, possibly suggesting that bluer small particles were more rapidly accelerated out of frame by the effects of solar radiation pressure, leaving redder large particles.

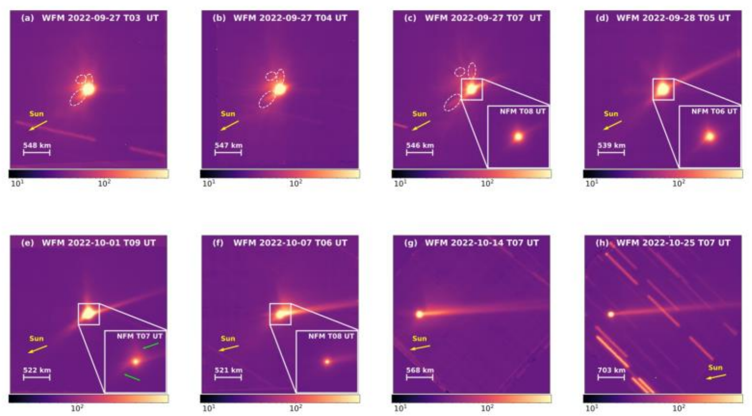

Figure 1. White light images from Sep 27 to Oct 25, showing the tail, ejecta cone, spirals (green arrows), and notable clumps (white ellipses).

References: [1] A. S. Rivkin et al., (2021), *Planet. Sci. J.*, vol. 2, no. 5. [2] A. F. Cheng et al. (2020) *Icarus*, vol. 352, p. 113989. [3] R. Bacon et al. (2010) *SPIE.*, vol 7735, no. 08. [4] C. Opitom et al. (2023), *Astron. & Astrophys. J.* [5] J.-Y. Li et al. (2023), *Nature.*

The orbital period change of asteroid Dimorphos as a result of DART mission impact

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On 26th September 2022 NASA conducted first planetary defence test using the DART spacecraft. The probe hit a small moon Dimorphos orbiting a near-Earth asteroid Didymos. One of the principal mission aims was to change orbital period of Dimorphos in the asteroid system in a measurable way [1], and it was a great success. The collision aftermath was closely monitored from space and ground, including with the Danish 1.54m telescope in Chile. The global observing campaign was designed for determining the period change and monitoring post-impact ejecta. The orbital change was measured to be -33±1 min, and confirmed with two different observational methods: the optical observations and Doppler-delay radar imaging [2]. We present Edinburgh's contribution to the optical observing campaign with the Danish telescope and discuss the period change measurement.

[1] Rivkin et al., "The Double Asteroid Redirection Test (DART): Planetary Defense Investigations and Requirements", The Planetary Science Journal, 2, 24pp, 2021.
[2] Thomas et al., "Orbital Period Change of Dimorphos Due to the DART Kinetic Impact", Nature, In Press, 2023.

Autonomous navigation around Didymos using CNN-based Image Processing.

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The Asteroid Impact and Deflection Assessment (AIDA) is an international collaboration between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) aimed to investigate the binary asteroid system (65803) Didymos and to demonstrate asteroid deflection technique with kinetic impact. NASA launched the impactor while ESA will launch Hera, an asteroid rendezvous mission that will observe the impact effects closely.

The proximity operations of Hera's spacecraft around the target body rely on an autonomous optical navigation system that collects on-board visual information to estimate the relative position and attitude of the spacecraft with respect to the asteroid. The core component of this navigation method is the Image Processing (IP) algorithm that extracts optical observables from images captured by the spacecraft's on-board Asteroid Framing Camera (AFC). In this work, we present a pipeline to estimate the position of Hera's spacecraft around binary asteroid system Didymos during the proximity operations using a Convolutional Neural Networks (CNN)-based IP algorithm. The proposed algorithm uses the images captured with the AFC camera to estimate the pixel position of the centroids of the primary and the secondary, to estimate the pseudo-range from the target, to estimate the Sun phase angle and to solve the pose estimation of the secondary during the very close fly-bys of Hera's spacecraft.

The training, validation and testing datasets are generated with the software Planet and Asteroid Natural scene Generation Utility (PANGU). The High-Resolution Network (HRNet) is used as CNN architecture as it represents the state-of-the-art technology in keypoint detection.

The HRNet-based IP algorithm estimates the position and the velocity of Hera's spacecraft with respect to the target with an error of around 300 m and 2 cm/s.

The ESA Hera Mission: Completing the Experiment

Alan Fitzsimmons on behalf of the Hera mission team.

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On 26 September 2022 the DART spacecraft successfully impacted the small asteroid Dimorphos in the first real-life test of kinetic impactor technology. Subsequent observations by a multitude of Earth-based facilities confirmed the effectiveness of DART in changing the orbital period of Dimorphos by 33 minutes. But our precise understanding of what happened in the impact is hampered by the limited resolution of these data and the (albeit spectacular) post-impact images from LICIACube. Many of the remaining unknowns will be addressed by the Hera mission. Scheduled for launch in October 2024, it will rendezvous with Didymos/Dimorphos at the start of 2027 and spend at least 6 months observing the system in fine detail. The primary goals are to measure the precise mass of Dimorphos and the structure of the post-impact site of DART, measure any dynamical effects due to the impact, and characterise the surface and interior of Dimorphos. This will be achieved not only with instrumentation on Hera, but also with the two cubesats Juventas and Milani. This talk will describe the current status of the mission, the current planned operations, and how the Hera Mission will lead to an improved capability for planetary defence.

Lunch time extra talk
Making the most of simulations and visualisations

Jacob Kegerreis[1,2]*, Tom Sandnes[1], Vince Eke[1], Richard Massey[1].
[1]*Durham University,* [2]*NASA Ames.* Email: jacob.kegerreis@durham.ac.uk

While we as scientists would love to run experiments to study what really happens in large-scale impacts, the unfortunately sub-planetary sizes of current labs mean that full-size experiments are usually relegated to numerical simulations. Understanding the codes we use and the supercomputers that run them is therefore crucial for performing reliable experiments at the highest possible speeds and resolutions. Once the numerical results have been obtained, visualisations of them are often limited to simplified projections, or handed over to inconsistent artistic interpretations. Improving the visualisation of numerical results can enhance communication and engagement with both the scientific and public communities. We have developed the open-source code SWIFT [1] to run smoothed particle hydrodynamics (SPH) simulations of giant and now smaller-scale impacts with over two orders of magnitude higher resolution than the current standard. I will discuss the intuitive ways that SWIFT takes advantage of modern supercomputing architectures to enable this jump, how recent work has improved previous shortcomings in the SPH method, and how flexible tools like SPH can be applied to a wide variety of impact topics. Using a Moon-forming impact simulation as an example, I will then discuss how popular VFX programs like Houdini can be used to create impactful visualisations [2] that remain directly driven by the simulation data.

Fig. 1: An example visualisation of 3D SPH simulation data using Houdini, showing a mid-impact snapshot from a Moon-forming collision. The rendered colour, opacity, and emission of the particles and volumes are set by the SPH material, density, and thermal energy. An animation is available at https://youtu.be/AQmeomxvokM, and a mini 'VFX breakdown' at https://youtu.be/rbskVhtWIco.

[1] https://swift.dur.ac.uk/
[2] These example animations gained >3.5 M views with the press release for our paper, and another Houdini visualisation of the data was used in the recent Our Universe documentary.

Afternoon session

The Legal and Policy aspects of Planetary Defence

Guest speaker: Alissa Haddaji, Harvard.

Profile: Professor Alissa J. Haddaji is the United Nations' mandated SMPAG Ad-Hoc Legal Working Group on Planetary Defense coordinator. She also serves as the vice-chair of the International Astronautical Federation's Near Earth Object & Planetary Defense Committee. She is an adjunct Professor in Space Law, Policy and Ethics. She is the founder and director of The Space Consortium at Harvard & MIT, and of Space Week at Harvard. She created and taught the Space Law, Policy and Ethics curriculum at Harvard College, Harvard Law School, Boston College Law School and University Paris-Saclay "M2 New Space". Prof. Haddaji specializes in International Space Threat Management (Planetary Protection/Planetary Defense).

Source: https://space4women.unoosa.org/content/2020-mentor-alissa-j-haddaji

No abstract is available for this talk.

The UK Fireball Alliance – building an all-sky UK meteor observatory

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Monitoring the skies for meteors and fireballs that occur when extraterrestrial objects enter Earth's atmosphere is crucial for understanding the evolution of the Solar System and developing robust plans for planetary defence. The UK Fireball Alliance (UKFAll) was established in 2018 and is a collaboration of camera networks that aims to record meteors and fireballs and recover freshly-fallen meteorites in the UK [1]. The UKFAll networks can make 1000's of single-station detections each night, with multiple observations of the same event used to calculate velocities, mass, trajectories, and orbits of incoming dust and rocks. In 2021, data from the UKFAll was crucial to calculating the pre-atmospheric orbit, initial meteoroid size and mass, and fall position of the Winchcombe meteorite [2]. I will talk about efforts to upgrade and develop a nationwide meteor observatory that has the potential to make significant contributions to our understanding of small body populations, solar system geology, and astronomical and meteorological monitoring programmes.

[1] ukfall.org.uk
[2] King, Daly et al. (2022) *Sci. Adv.* **8**:eabq3925.

Meteoritic event recorded in Antarctic ice – part 2: further exploring the BIT-58 debris layer and its implications for the impact record of Earth

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Airbursts are the result of the disruption of asteroids less than 200m in size in the lower atmosphere and represent the most frequent type of cosmic impacts resulting in significant damage at ground level (Artemieva et al., 2020). A breakthrough in the study of past airbursts is the recent discovery on top of the Walnumfjellet nunatak of impact spherules produced during a large low-altitude airburst, termed touchdown event, over Antarctica ca. 430 kyrs ago (Van Ginneken et al., 2021). This provided new insights into airbursts that until then remained unidentified in the geological record. A major question arising from this discovery is whether this was an isolated occurrence resulting from unique conditions or rather that such products are common during large airbursts. This, in turn, allows to explore if airburst residues are common in the geological record.

The BIT-58 impact debris layer found near Allan Hills in Antarctica, and first reported by Harvey et al. (1998), essentially consists of spherules and angular fragments that were identified as ablation debris of a large H-group ordinary chondrite based on their major element chemistry and levels of cosmogenic nuclide. Notably, the unique set of textures displayed by the BIT-58 particles are comparable to those from the Walnumfjellet nunatak, suggesting a similar origin. To work out the petrogenesis of BIT-58, we adopted the same methodology as Van Ginneken et al. (2021) by analysing the major element compositions of individual mineral phases, mostly olivine and cosmic spinel, and the oxygen isotope signatures of a selection of BIT-58 particles.

We report the first results of this study, which has implications for the identification of airburst residues in the geological record and, by extension, our ability to better understand what is now considered as the principal cosmic threat to human civilization.

References: Artemieva N. A. and Shuvalov V. V. 2016. Annu. Rev. Earth Planet. Sci. 44, 37–56; Harvey et al. 1998. Geology 26, 607–610; Van Ginneken et al. 2021. Sci. Adv. 7, abc1008.

2023 PDC EXERCISE: GLOBAL TSUNAMI FROM LAND OR OCEAN IMPACT

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Keywords: *Lamb Wave, tsunami, meteotsunami, Proudman resonance*

ABSTRACT

For the 2017 PDC we modeled the production of asteroid–generated tsunami by direct coupling of the pressure wave, analogous to the means by which a moving weather front can generate a meteotsunami. We used the CTH hydrocode to simulate various airburst scenarios to provide time dependent boundary conditions as input to shallow-water wave propagation codes. The strongest and most destructive weather-driven meteotsunami are generated by atmospheric pressure oscillations with amplitudes of only a few hPa, corresponding to changes in sea level of a few cm. The resulting wave is strongest when there is a resonance between the ocean and the atmospheric forcing. A Proudman resonance takes place when the atmospheric disturbance translational speed (U) equals the longwave phase speed c = $\sqrt{gh}$ of the shallow water wave. Coupling is strongest when the Froude number (Fr=U/c) is unity.

Using the parameters for the impact associated with the 2023 PDC exercise, we simulated the blast and resulting global meteotsunami from land impacts in Dallas and Jebba, Nigeria. We have shown that the resulting global tsunami contribute significantly to the destruction. Because the coupling and focusing of the tsunami depend upon the details of ocean bathymetry and its relationship to the source, the damage can be greatest in unexpected places across the globe. We propose ensemble simulations of Lamb-wave generated tsunami for impact locations spanning the planet to provide maps to enable rapid tsunami warnings in the event of a pending or unexpected NEO impact.

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Intelligent Decision Support System for NEO Impact Scenarios Identification and Deflection Strategies Selection under Uncertainty

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Keywords: *Asteroid Deflection, Machine Learning, Robust Optimization, Epistemic Uncertainty, Impact Probability*

ABSTRACT

Near Earth Objects (NEO) impact poses a major threaten to all life forms on Earth. In the planning and decision making process that precedes the implementation of a NEO deflection mission, such as identifying hazardous NEO and selecting deflection strategies, there is a considerable amount of uncertainty affecting any decision. Computing a robust and globally optimal solution under mixed aleatory and epistemic uncertainty is computationally expensive and the cost rapidly grows with the number of uncertain quantities. To quickly respond to a NEO impact scenario, an Intelligent Decision Support System (IDSS) is proposed to automatically decide if a deflection mission is necessary, and then select the most effective deflection strategy. IDSS consists of two sub-systems: the first one is named as NEO Impact Scenarios Identifier, and the second one is named as NEO Deflection Strategies Selector. The input to the NEO Impact Scenarios Identifier is the warning time, the orbital parameters and the diameter of the NEO and the corresponding uncertainties. According to the post-deflection impact probability and the corresponding confidence, the output is the decision of action: the deflection is needed, no deflection is needed, or more measurements need to be obtained before making any decision. If the deflection is needed, the NEO Deflection Strategies Selector is activated to output the deflection strategies that are more likely to offer a successful deflection.

The training dataset is produced by generating thousands of virtual impact scenarios, sampled from the real distribution of Near-Earth Objects. A robust optimization is performed, under mixed aleatory/epistemic uncertainties, with five different deflection strategies (Nuclear Explosion Device, Kinetic Impactor, Laser Ablation, Gravity Tractor and Ion Beam Shepherd).

We demonstrate the capabilities of Random Forest at classifying impact scenarios and deflection strategies. Simulation results suggest that once trained the IDSS, does not require re-running expensive simulations and is, therefore, suitable for the rapid prescreening the impact scenarios and deflection options.

THE RISK ASSESSMENT PILLAR AT ESA'S PLANETARY DEFENCE OFFICE

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One of the main goals of the ESA's NEO Coordination Centre (NEOCC) is the computation of the orbits of near-Earth objects (NEOs) and their probability of impact with the Earth. These activities are carried out by the Risk Assessment Pillar, one of the three pillars of ESA's Planetary Defence Office.

To achieve this goal, the NEOCC operates Aegis, an automated orbit determination and impact monitoring system developed by SpaceDyS s.r.l. through industrial contracts from ESA. The Aegis system updates astrometric data of asteroids from the Minor Planet Center on a daily basis, and provides a catalogue of NEOs which comprises orbits with their uncertainties, some physical properties, observations and residuals, close approaches and ephemerides. More importantly, it computes the impact probabilities of NEOs in the next 100 years, and the results are collected in the so-called Risk List. All the data generated is publicly available in the NEOCC web-portal. Aegis is used to produce the input of several tools and services available in the portal, such as the orbit and fly-by visualizers, ephemerides requests, and all the tools of the NEO Toolkit.

The Risk Assessment Pillar is also operating and developing the Meerkat tool, an automated monitoring system for imminent impactors. Since its introduction at the PDC 2021, Meerkat successfully detected the last three impactors, 2022 EB5, 2022 WJ1, and 2023 CX1, and it has been improved in terms of stability, reliability, and performance. In December 2022, Meerkat started sending its results through an open mailing list to the Planetary Defence community.

INVESTIGATING THE EJECTION OF LOW-PRESSURE MATERIAL FROM EARTH TO THE MOON USING NUMERICAL MODELLING.

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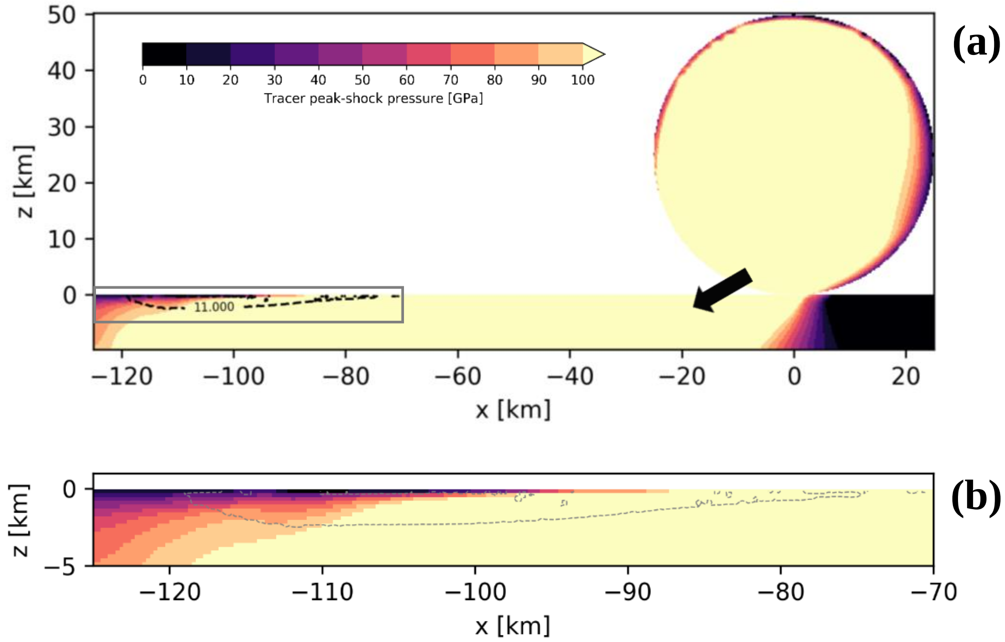

Figure 1: Cross section pressure plot of ejecta for a simulation of a 50 km diameter impactor striking Earth at 30° to the surface and at 20 km s^{-1}. The low-pressure zone from (a) is highlighted in (b). The direction of impact is from right to left (black arrow). Dashed lines show the volume of target ejected at >11 km s^{-1}.

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Basin-forming, hypervelocity impacts striking Earth [1] could potentially eject terrestrial material at velocities great enough to surpass escape velocity and take up Moon-crossing orbits [2,3,4]. If identified, relatively unshocked terrestrial material on the Moon may provide insights into the early Earth that the Earth itself no longer records [5]. Theoretical estimates using extrapolation of an analytical model of spallation [6, 7] suggest that a mass of ejecta equivalent to as much as 10^{-5} to 10^{-2} of the original impactor's mass (M_i) may escape Earth's gravity without exceeding a shock pressure of 10 GPa [2]. Using iSALE-3D [8,9], we present high-resolution, 3D simulations that resolve the fraction of ejecta with both high speed and low pressure, to show that low-shock ejection is possible from Earth. A 50 km diameter projectile was modelled striking Earth at angles of 30°, 45°, and 60° to the surface (assumed to be horizontal) and at velocities of 20, 30, and 55 km s^{-1}. Simulations were run at a resolution of 100 cells per projectile radius (CPPR) to adequately resolve low-pressure, high-velocity ejected material. Launch speed and peak pressure of ejecta were recorded by tracer particles placed in each cell. An ejection velocity threshold of 11 km s^{-1} was used as an estimate for the launch speed needed to reach a Moon crossing orbit. Of the scenarios considered, only those with an impact angle of 30° resulted in escaping ejecta that experienced pressures <10 GPa. The mass of low-pressure, high-velocity material ejected is on the order of 10^{-4} to 10^{-5} M_i, depending on the impact conditions, consistent with previous estimates. In the simulation with the largest mass of low-pressure material (20 km s^{-1} impact velocity, 30° impact angle), ~1.68×10^{-4} M_i of target material is ejected at velocities >11 km s^{-1} and peak pressures <10 GPa. This material originates from the near-surface, over 100 km from the impact zone (Figure 1).

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References: [1] Marchi S. et al. (2014) *Nature,* 511, 578-582. [2] Armstrong J. et al. (2002) *Icarus*, 160, 183-196. [3] Armstrong J. (2010) *Earth, Moon, & Planets*, 107, 43-54. [4] Beech M. et al. (2019) *AJAA*, 7, 1-9. [5] Halim S. H. et al. (2021) *Icarus,* 354, 114026. [6] Melosh H. J. (1984) *Icarus,* 59, 234-260. [7] Melosh H. J. (1985) *Geology,* 13, 144-148. [8] Elbeshausen D. et al. (2009) *Icarus,* 204, 716-731. [9] Elbeshausen D. & Wünnemann K. (2011) *Proc. 11th Hypervelocity Impact Symp,* 287.

Immediate origin of the Moon as a post-impact satellite

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At the most extreme end of the scale for impacts onto the Earth is the collision that formed the Moon. We study these giant impacts using the same numerical tools that can be applied to the smaller scales of crater-forming impacts. The Moon is traditionally thought to have slowly coalesced from the debris ejected by a collision near the end of the Earth's accretion. However, such models struggle to explain the similar isotopic compositions of Earth and lunar rocks at the same time as the system's angular momentum, and the details of potential impact scenarios are hotly debated. Above a high resolution threshold for simulations, we find that giant impacts can immediately place a satellite with similar mass and iron content to the Moon into orbit far outside the Earth's Roche limit. Even satellites that initially pass within the Roche limit can reliably and predictably survive, by being partially stripped then torqued onto wider, stable orbits. Furthermore, the outer layers of these directly formed satellites are molten over cooler interiors and are composed of around 60% proto-Earth material. This could alleviate the tension between the Moon's Earth-like isotopic composition and the different signature expected for the impactor. Immediate formation opens up new options for the Moon's early orbit and evolution, including the possibility of a highly tilted orbit to explain the lunar inclination, and offers a simpler, single-stage scenario for the impact origin of the Moon[1].

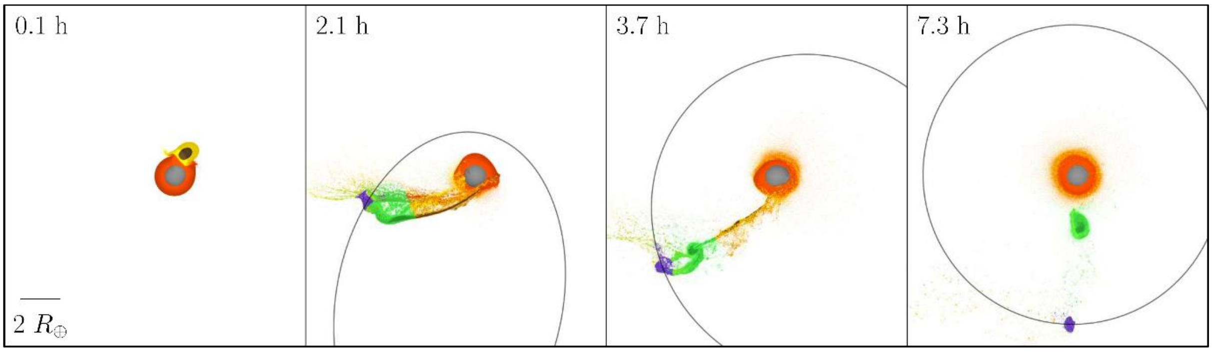

Fig. 1: Illustrative cross-sections of early-time snapshots from a simulation where a satellite is placed directly onto a wide orbit. The particles that will form the satellite and inner remnant are highlighted in purple and green. The black lines show the estimated orbit. Grey and orange show the proto-Earth's core and mantle material respectively, and brown and yellow the same for Theia. The colour luminosity varies slightly with the internal energy. The annotated time is measured from first contact, the simulation began at –1 hours. An animation is available at http://icc.dur.ac.uk/giant_impacts/moon_wide_orbit_slice.mp4, and at http://icc.dur.ac.uk/giant_impacts/moon_wide_orbit_houdini.mp4 for the same SPH data rendered in 3D.

[1] Kegerreis et al. 2022, Astrophys. J. Lett., 937, L40.