Outcome of collisions in the Early Outer Solar System

ISSI Team call 2018
Jean-Baptiste Vincent & Collaborators

Abstract

The processes leading to the formation of planetary systems leave behind a significant mass of small bodies orbiting at large heliocentric distance, up to 35 Earth masses depending on the models (Tsiganis et al., 2005), observed around 20% of Sun-like stars. It is established that those bodies play an important role in the migration of gas giants away from their stars and may be necessary for life to develop on the smaller planets. Yet, the conditions within these primitive populations are not well understood, especially their collisional environment.

In the last decade, space missions have brought fascinating new data which challenge our concepts of impacts in the Early Solar System. The mission Rosetta at comet 67P, for instance, has revealed a complex cometary world where collisions, from small to catastrophic, played a significant role. Recent work suggests that the topography of cometary nuclei and potential layering are shaped by processes which are primarily ancient. On a larger scale, dynamical simulations argue that objects like the Jupiter Family Comets may have been totally disrupted by catastrophic collisions. While models show that the high porosity and volatile content of cometary nuclei would survive such impacts, it is not clear whether the deeper structural features like layers can be preserved. From the same data set, different authors (Blum, Davidsson, Morbidelli, Rickman) come to different conclusions with respect to collisions in the early outer planetary system. Furthermore, different modeling approaches (de Niem, Jutzi, Schwartz) lead to distinct results.

The concept of this working group is to bring together for the first time European experts on collisions and cometary morphology. Over the last few years, modelers have developed new numerical simulations which are now able to properly treat cometary-like material. In parallel, thanks to Rosetta mission, small bodies morphologists have a much better understanding of the type of landform that can exist on comets, and measurements of the material physical properties. By combining our expertise, we aim to assess the role of impacts in the formation and evolution of comets, as well as properly benchmarking and comparing the different modeling approaches. This work will lead to a new understanding of impact processes in the Solar System history and provide very strong constraints on the formation and evolution of objects at large heliocentric distance, with applications beyond our own System.

1 Scientific rationale and goals of the project

The last decade has seen major shifts of paradigm in our understanding of Solar System formation and evolution, in particular regarding the role of small celestial bodies such as comets and asteroids. While these objects appear now as minor components of our System, it was not always like that. The prevalent theory regarding the early phase of planet formation in our System postulates that small bodies represented the third component in mass in the planetary disk after Jupiter and Saturn (Morbidelli et al., 2008). It is now widely accepted that the presence of such a massive debris disk beyond the current orbit of Neptune is partly responsible for the migration of the giant planets and cataclysmic events in the early Solar System. This led to the delivery of a significant amount of material to the Inner planets, now found in water and organic material on Earth. For instance, recent results from ESA's Rosetta mission show that up to 20% of the xenon in our atmosphere may have a cometary origin (Marty et al., 2017). Such populations of small bodies are not limited to our System. In addition to direct imaging by the Hubble Space Telescope for about 10 stars, infra-red observations by IRAS also suggest that 15%-20% of main sequence stars in our galaxy are surrounded by a massive disk of planetesimals (Trilling et al., 2007).

Yet, despite their ubiquitous presence in planetary systems, and their fundamental role in our early history, small bodies remain poorly understood. Their formation and evolution mechanisms are heavily debated in the planetary community. Planetesimal formation models depend strongly on the actual effects of impacts in the Kuiper Belt, currently under-constrained. The Nice model (Morbidelli, 2008) and more recent work (Rickman et al., 2015) postulate that comets would have been destroyed by early collisions and what we observe now are re-accreted fragments from that phase. While the high collisional rate seems compatible with recent observations (e.g. New Horizons at Pluto), the occurence of events leading to disruption is not confirmed.

Some numerical modeling has been done to try to address this problem. In 2013, Vincent et al (PSS) published a review paper summarizing everything we knew about impacts on cometary material in the current Solar System (Vincent et al., 2015a). In this work we also proposed new scaling laws and a numerical model based on the iSALE shock physics code (Amsden et al., 1980; Collins et al., 2004; Wünnemann et al., 2006) to describe better high velocity impacts of asteroid-type objects on cometary material. Our results have been confirmed by the space missions Deep Impact and Rosetta. However, our model was limited to the current Solar System, and we realize now that the impact rate in the primitive belt could have been quite different than assumed by previous models, and could have modified comets significantly. In 2012, [Campo Bagatin and Benavidez, 2012] studied the collisional evolution of the trans-neptunian region as constrained by current observational surveys [(Petit et. al., CFEPS, 2011)] and dynamical evolution models.

In the last few years, De Niem et al (DLR Berlin) have developed a completely new numerical model (specifically aiming) at simulating collisions of porous planetesimals in their primitive environment. The model (de Niem et al., 2018) has been tested against laboratory experiments and scaling laws and is now ready to be applied to in-situ data sets.

M. Jutzi and collaborators have published two articles (Jutzi & Benz, 2017; Jutzi et al., 2017) investigating the effects of collisions on the bi-lobed structure of comets, which is a rather common morphology. They conclude that an object like 67P could have been formed by a later collision in the last 1GY.

This year, Schwartz et al. (2018) have shown that it is possible to disrupt and reaccrete a comet through a catastrophic disruption, while preserving its high porosity and volatile content, a question often raised against this hypothesis. Similarly, Campo Bagatin et al. (2018) and colleagues showed that the process of reaccumulation following collisions (shattering or on pre-shattered bodies) can explain macroporosity estimated for asteroids and comets, as well most of their shapes.

All these models convincingly show that the disruption of a comet progenitor would leave behind fragments which may reaccrete into a body sharing some of the properties observed on comets. Yet, it is not clear what would happen in case of repeated impacts (probability not negligible in the higher-mass models of the primitive disk). In addition, the growing evidence that comets are layered (Massironi et al., 2015; Penasa et al., 2017) would suggest that simulations of impacts would need to take the presence of layers into account.

On small scale, recent work by Vincent et al. (2017) on the erosional evolution of Jupiter Family Comets strongly suggests that the morphology we observe now is strongly shaped by primitive events while the comet was evolving in its source region, which modified the topography long before the nucleus entered the Inner Solar System. For instance, it may very well be that the large pits discovered on 67P (Vincent et al., 2015b) are linked to primitive impacts. If this is correct, it would modify our understanding of the first hundreds of millions years of the Solar System, as these impacts could imply a denser environment, hence a large mass in the Kuiper belt. In turn, this would have consequences on the migration of the giant planets and the early transport of material in our system. Beyond the early work presented above, no further attempt has yet been made to model how the structure and composition of comets are affected by small impacts leaving traces in the 100 m scale on the nucleus surface.

Our ISSI team will investigate these collisions at all scales, and report on what they mean for the structural and chemical evolution of comets. If we show that small impacts created the early topography, we will finally have a measure of the early population density in the Kuiper Belt, a crucial parameter for models of the Solar System. On the other hand, if we show that comets have been fully destroyed by impacts, as suggested by Rickman et al. (2015), our model will lead to a better description of the inner structure of these objects, potentially answering the homogeneous vs heterogeneous interior debate.

Additionally, by modeling the heat transfer upon impacts with our codes, and taking into account the chemical layering of comets suggested by the Rosetta mission (several papers from ROSINA, OSIRIS, VIRTIS instruments), we will be able to assess whether significant chemical evolution could have taken place in that phase. For instance an early conversion of amorphous ice to crystalline ice, if triggered by impacts, could lead to a greatly different shape for the craters due to additional heat released by phase transition. This will affect the scaling laws relating crater size to projectile diameter, and therefore can completely challenge our assumptions on the early belt population derived from crater analysis.

By modeling collisions like those comets may have experienced in the primitive Outer Solar System, and reconstructing the history of these objects we will set new constraints on the early dynamics at large heliocentric distances. This is fundamental to reconstruct the environment before and during planetary migrations.

2 Program and Schedule

We plan to organize our work within the full 18 months period allocated by ISSI. Most of the numerical work will be carried on at our respective institutes, but team meetings are fundamental to agree on a common set of parameters to be used by each model, and carefully compare the outcome of our numerical experiments with the morphological evidence from Rosetta and other mission and for discussion and interpretation of results.

A tentative schedule would be as follows:

- Meeting 1, late 2018: review of the current team knowledge on cometary morphology, status of the various numerical codes, decision on a few benchmarking tests.
- Meeting 2, summer 2019: results of the benchmarking, progress update on morphological analysis, set up of real case scenarios for the various types of impacts a comet may have experienced, first layout of the papers.
- Meeting 3, late 2019: finalization of our results, and associated publications.

Communication within the team in between our meetings will be organized via monthly teleconferences organized by the team Coordinator. A website will be set up in collaboration with ISSI to share publicly the results of our team. We will also host a private section where the team presentations and work in progress will be available to all members for the duration of the project.

In addition to the ISSI meetings, we will have informal gatherings at upcoming conferences to discuss the current project. As many of us are attending the 9th "Catastrophic Disruption" workshop in Kobe, Japan, this May, we will use the opportunity to discuss the availability of young scientists who could be associated to the team.

3 Output from the ISSI team

Beyond the final report to be provided to ISSI, our baseline is to work in parallel on at least three main manuscripts, to be submitted to peer-reviewed journals.

- Review paper "Craters on comets II" led by JB. Vincent addressing the many changes in our concepts of cometary cratering since the first review published in 2013. This will lead to drawing new conclusions on formation theories, from the constraints brought by Rosetta and so far not discussed consistently.
- Paper on "Layers and cratering" led by L. Penasa, on the relation between the apparent layering of Jupiter Family Comets and ancient impacts. What happens when layered objects collide ? Can layer be explained by low-velocity impacts (Belton et al., 2007).
- A "Benchmarking" paper coordinated by P. Michel comparing the output of all models for one or more well defined cases of impact-like features on comets. This is a more technical paper, but very important for the community.

4 ISSI added value

Due to its strong reputation in promoting excellent space science, and a central location in Europe, we believe ISSI Bern is a natural partner for our project. Moreover, Bern is known worldwide for impact studies, as some of the pioneers of impact modeling applied to Solar System objects have a position in Bern. Most of the team members have worked or are already working with ISSI and colleagues in Bern, and we know that the support provided by ISSI is exactly what we need for our group to succeed. Your logistic help will enable members of 5 different ESA member states to engage in direct exchange of ideas and expertise over a particularly important topic. This will speed up considerably our scientific progress.

It is understood that team members are individually funded by their home institutions for the whole duration of the project. We do request the standard ISSI funding support for the living expenses while in Bern, and the team coordinator travel support. As for facilities, we request the usual meeting equipment: a room with internet access, projector, a white board.

5 Team description and responsibilities

The team comprises 10 scientists from 5 different countries, with multidisciplinary expertise on the topics described above. Half of the team is younger than 40 years old, yet everyone has many publications on the topics relevant to this project.

Jean-Baptiste Vincent	DLR Institute for Planetary Research	Germany
Paula Benavidez	University of Alicante	Spain
Adriano Campo-Bagatin	University of Alicante	Spain
Martin Jutzi	University of Bern	Switzerland
Ekkehard Kuehrt	DLR Institute for Planetary Research	Germany
Patrick Michel	Laboratoire Lagrange - OCA Nice	France
Detlef de Niem	DLR Institute for Planetary Research	Germany
Nilda Oklay	DLR Institute for Planetary Research	Germany
Luca Penasa	University of Padova	Italy
Kai Wünnemann	Naturkunde Museum Berlin	Germany

Note: In addition to this core team, A. Morbidelli (OCA, France) and B. Davidsson (JPL, USA), experts in dynamics, offered to provide some advice and help us discuss the implications of our work on their models of the Early Solar System.

The team brings together experts in cometary morphology, impacts and catastrophic disruptions of small bodies, formation and evolution of the Solar System. Most team members have a multidisciplinary background particularly relevant to the project.

Our group is also conceived as a bridge between the Rosetta and impact modeling communities. For political reasons beyond our control, the modelers did not have access to the high resolution imaging data during the active phase of the mission and therefore could not get the full picture of cometary morphology and surface evolution. Likewise, the same issues forced Rosetta scientists to draw conclusions without being able to test all hypotheses with state-of-the art numerical models.

At the time of submitting this proposal, the proprietary period has ended and all the relevant Rosetta data needed for our analysis is publicly available. In addition, JB. Vincent, E. Kuehrt, N. Oklay, and L. Penasa are Co-Investigators on several Rosetta instruments, most notably the OSIRIS cameras, and have a full understanding of the different types of data. The Rosetta Co-Is and associates will provide not only images of potential impact-related morphologies, but also their expertise and current models on cometary morphology, evolution, and material properties. We also have access to compositional data from the ROSINA instrument, and will use them to address how impacts may have affected the distribution of volatile species in the nucleus.

This data will serve as input parameters to the modelers in our team. Only very few attempts have been made to model impacts on comets, due to the poor knowledge of the material properties, especially the various strength parameters and the equation of state. While uncertainties remain as to what comets are really made of, our knowledge has significantly improved and the Rosetta data provide the perfect opportunity to compare the outcome of vastly different numerical models. This ISSI group will involve experts and lead developers of the most advanced impact codes available worldwide: pkdgrav particle code (P. Benavidez, A. Campo-Bagatin), iSALE hydrocode (N. Oklay, K. Wünnemann), Bern-smooth particle hydrodynamics code (M. Jutzi), and Berlin-hydrocode (D. de Niem).

All together, this team is very well suited to address the challenging scientific issue of collisions at large heliocentric distances in the Early Solar system.

Appendix A: References

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Penasa L., et al., 2017, Monthly Notices of the Royal Astronomical Society, 469, S741

Rickman H., et al., 2015, Astronomy & Astrophysics, 583, A44

Schwartz S. R., Michel P., Jutzi M., Marchi S., Zhang Y., Richardson D. C., 2018, Nature Astronomy

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Vincent J.-B., Oklay N., Marchi S., Höfner S., Sierks H., 2015a, Planetary and Space Science, 107, 53

Vincent J.-B., et al., 2015b, Nature, 523, 63

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Wünnemann K., Collins G., Melosh H., 2006, Icarus, 180, 514

de Niem D., Kührt E., Hviid S., Davidsson B., 2018, Icarus, 301, 196

Appendix B: Contact sheet and CVs of team members

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Luca Penasa Center of Studies and Activities for Space, CISAS, 'G.Colombo', University of Padova, Via Venezia 15, I-35131 Padova, Italy email: luca.penasa@gmail.com tel: +39 49 827 5111	**Kai Wünnemann** Museum für Naturkunde, Leibniz-Institut für Evolutions und Biodiversitäts-forschung, Invalidenstraße 43, 10115 Berlin, Germany email: kai.wuennemann@mfn-berlin.de tel: +49 30 2093 8857

NAME, First Name: **VINCENT, Jean-Baptiste**

Affiliation: German Aerospace Center (DLR), Institute of Planetary Research

Role in the project: Team leader, cometary morphology, theoretical models of activity and surface evolution of small bodies surface, impact modeling with scaling laws.

Current responsibilities:

- Post-doctoral researcher at DLR Berlin, Germany.
- Co-Investigator on the OSIRIS cameras (ESA's Rosetta mission).
- Co-Investigator on ESA's AIM and NASA's DART spacecraft in the joint AIDA mission.
- Co-Investigator on the New Frontiers comet sample return proposal CAESAR.
- Co-Investigator on the MASCOT lander (Hayabusa 2 mission, JAXA).
- Member of the DLR associate team to NASA's Lucy mission to Trojans.
- Coordinator of the working group on "Evolution of cometary nuclei" in the EU-funded MiARD project.

Former Positions:

- Post-doctoral researcher at Max Planck Institute for Solar System Research, Göttingen, Germany.
- Co-Investigator on the OSIRIS cameras (ESA's Rosetta mission).
- Coordinator of the OSIRIS working group on cometary activity.
- Science Planning lead for OSIRIS.
- Associate scientist with the FC camera (NASA's Dawn mission).

Education:

- M.Sc. in Astrophysics and Planetology (2005, Toulouse, France).
- M.Sc. in Space Engineering and Instrumentation (2006, Toulouse, France).
- PhD at TU Braunschweig, (2010, Braunschweig, Germany).

Services in National and/or International Committees (last ones): Reviewer for many journals (A&A, Icarus, PSS, MNRAS).

Honors:

- 2007: International Max Planck Research School PhD scholarship.
- 2010: A&A highlight for my paper on "A numerical model of cometary dust coma. structures: application to comet 9P/Tempel 1".
- 2013: NASA award for my scientific contribution to the Dawn mission.
- 2017: NCU-Delta Young Astronomer Lectureship Award for "outstanding achievements in astronomy research", National Central University of Taïwan..
- 2017: ESA Award for "outstanding contribution to the Rosetta mission".

Selected Publications:

- **J.-B. Vincent**, S.F. Hviid, S. Mottola, E. Kuehrt, F. Preusker, F. Scholten, H. U. Keller, N. Oklay, D. de Niem, & the OSIRIS team, Constraints on cometary surface evolution derived from a statistical analysis of 67P's topography, MNRAS (June 2017)
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- **J.-B. Vincent**, N. Oklay, M. Pajola, S. Hoefner, H. Sierks, X. Hu & the OSIRIS team, Are fractured cliffs the source of cometary dust jets ? Insights from OSIRIS/Rosetta at 67P, Astronomy & Astrophysics, Volume 587, A14, (2016)
- **J.-B. Vincent**, D. Bodewits, S. Besse, & the OSIRIS team, Large heterogeneities in comet 67P as revealed by active pits from sinkhole collapse, Nature, Volume 523, Issue 7558, pp.63-66 (2015)
- **J.-B. Vincent**, N. Oklay, S. Marchi, S. Hoefner, H. Sierks, Craters on comets, PSS, Volume 107, Pages 53-63 (2014)
- **J.-B. Vincent**, P. Schenk, A. Nathues, H. Sierks, M. Hoffmann, R. W. Gaskell, S. Marchi, D. P. O'Brien, M. Sykes, C. T. Russell, M. Fulchignoni, H. U. Keller, C. Raymond, E. Palmer, F. Preusker, Crater Depth-to-Diameter Distribution and Surface Properties of (4)Vesta, PSS, Volume 103, Pages 57-65 (2013)
- **J.-B. Vincent**, H. Boehnhardt, L.M. Lara, G.P. Tozzi, Z.Y. Lin, H. Sierks, Spin and activity of comet 67P/Churyumov-Gerasimenko, Astronomy & Astrophysics, January 2013, Volume 549, A121
- **J.-B. Vincent**, S. Besse, S. Marchi, H. Sierks, M. Massironi, and the OSIRIS team, Physical properties of craters on asteroid (21)Lutetia, PSS, Volume 66, Issue 1, June 2012
- **J.-B. Vincent**, H. Boehnhardt, L.M. Lara, A numerical model of cometary dust coma structures: application to comet 9P/Tempel 1, Astronomy & Astrophysics, March-April 2010, Volume 512, A60
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NAME, First Name: **BENAVIDEZ LOZANO, Paula Gabriela**

Affiliation: Universidad de Alicante

Role in the project: Expert in impact modeling with particle codes, and internal structure of small bodies.

Current position: Profesor Contratado Doctor (permanent position)

Former Position(s): Ayudante Doctor (Assistant Professor)

Education: PhD in Physics, Systems engineering and Signal theory

Services in National and/or International Committees (last ones):

- Scientific Organizing Committee: XIII Reunión científica de la Sociedad Española de Astronomía, July 2018.
- Local Organizing Committee: VII Workshop on Catastrophic Disruption in The Solar System, June 2007.

Selected Publications:

- **Benavidez, P. G.**; Durda, D. D.; Enke, B.; Bagatin, A. Campo; Richardson, D. C.; Asphaug, E.; Bottke, W. F. (2018). Impact simulation in the gravity regime: Exploring the effects of parent body size and internal structure. Icarus 304, 143-161
- Campo Bagatin, A.; Alemañ, R.; **Benavidez, P. G.**; Richardson, D. C. (2018). Internal structure of asteroid gravitational aggregates. Icarus, 302, 343-359
- Campo Bagatin, A.; **Benavidez, P. G.**; Ortiz, J. L.; Gil-Hutton, R. (2016). On the genesis of the Haumea system. MNRAS, 461, 2, 2060-2067
- Cibulková, H.; Brož, M.; **Benavidez, P. G.** (2014). A six-part collisional model of the main asteroid belt. Icarus, 241, 358-372
- Dell'Oro, A.; Campo Bagatin, A.; **Benavidez, P. G.**; Alemañ, R. A. (2013). Statistics of encounters in the trans-Neptunian region. A&A, 558, idA95
- Campo Bagatin, A.; Benavidez, **P. G.** (2012). Collisional evolution of trans-Neptunian object populations in a Nice model environment. MNRAS, 423, 2, 1254-1266
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- **Benavidez, P. G.**; Durda, Daniel D.; Enke, Brian L.; Bottke, William F.; Nesvorný, David; Richardson, Derek C.; Asphaug, Erik; Merline, William J. (2012). A comparison between rubble-pile and monolithic targets in impact simulations: Application to asteroid satellites and family size distributions. Icarus, 219, 1, 57-76
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NAME, First Name: **CAMPO BAGATIN, Adriano**

Affiliation: Universidad de Alicante (Spain).

Role in the project: Study of internal structure of comets by numerical modeling.

Current position: Titular de Universidad (since May 2010).

Former Position(s): Profesor Contratado Doctor (Univ. Alicante. March 2004- May 2010).

Education: Degree in Physics (Univ. Pisa, Italy); Ph.D in Physics (1997. Univ. Valencia, Spain).

Services in National and/or International Committees (last ones):

- SOC member 9th Catastrophic Disruption workshop (Kobe, Jp, 14th-17th/5/2018).
- SOC member Asteroids, Comets and Meteors conference (Montevideo, Uruguay, 10th-14th/4/2017).
- Project evaluator 'Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia' (National). 2017.
- NASA NSPIRES program evaluator, 2016.
- Coordination Committee of the AIDA space mission (since Jan. 2015).

Honors:

- Part of the team awarded with 'Premio La Vanguardia de la Ciencia'. 2018.
- Included in the 'Quo' magazine ranking: 'Las 101 mentes innovadoras de España'. 2015
- Asteroid 13722 Campobagatin (named by the IAU in 2002).

Selected Publications:

- **Campo Bagatin, A.** et al. Internal structure of asteroid gravitational aggregates. Icarus, 302, p. 343-359 (2018)
- Ortiz, J.l. **et al.**, The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation. Nature, 550, Issue 7675, pp. 219-223 (2017).
- **Campo Bagatin, A. et al.** On the genesis of the Haumea system. MNRAS, 461, Issue 2, p.2060-2067
- Michel P. **et al.**, Science case for the Asteroid Impact Mission (AIM): A component of the Asteroid Impact & Deflection Assessment (AIDA) mission. Advances in Space Research, Volume 57, Issue 12, p. 2529-2547 (2016)
- **Campo Bagatin, A.** and Benavidez, P.G. Collisional evolution of trans-Neptunian object populations in a Nice model environment. MNRAS, 423, Issue 2, pp. 1254-1266. (2012)

NAME, First Name: **JUTZI, Martin**

Affiliation: Physics Institute, University of Bern, Switzerland; NCCR Planets

Role in the project: Expert in numerical impact simulations, collisional evolution of cometary nuclei

Current position: Senior Researcher at University of Bern

Former Position(s): SNF Ambizione fellowship at University of Bern (2012-2015); Postdoc at University of California, Santa Cruz, US (2009-2011)

Education: PhD in Physics at University of Bern, Switzerland and University of Nice, France (2005-2009); Studies in Physics, Mathematics and Astronomy at the University of Bern (2000-2005)

Services in National and/or International Committees (last ones):

- Referee (ICARUS, A&A, Nature Geoscience, MNRAS)
- Member of the Swiss Society for Astrophysics and Astronomy

Honors:

- Fellowship for research in Japan by the Japan Society for the Promotion of Science (JSPS) (2016)
- Asteroid 25084 Jutzi (2014)
- MERAC Funding and Travel Award by the Swiss Society for Astrophysics and Astronomy (2013)
- Ambizione fellowship by the Swiss National Science Foundation (2012)

Selected Publications:

- Schwartz, S.R, Michel, P., **Jutzi, M.**, Marchi, S., Zhang, Y., Richardson, D.C. 2018. Catastrophic disruption as the origin of bilobate comets. Nature Astronomy.
- **Jutzi, M.**, W. Benz, A. Toliou, A. Morbidelli, R. Brasser. 2017. How primordial is the structure of comet 67P/C-G? *Astronomy and Astrophysics*, 597, A61.
- **Jutzi, M.**, W. Benz. 2017. Formation of bi-lobed shapes by sub-catastrophic collisions. *Astronomy and Astrophysics*, 597, A62.
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- **Jutzi, M.** 2015. SPH calculations of asteroid disruptions: the role of pressure dependent failure models. *Planetary and Space Science*, 107, 3.
- **Jutzi M.**, Asphaug, E., Gillet, P., Barrat, J.-A., Benz. W. 2013. The structure of the asteroid 4 Vesta as revealed by models of planet-scale collisions, *Nature*, 494, 207.

NAME, First Name: **KÜHRT, Ekkehard**

Affiliation: German Aerospace Center (DLR), Institute of Planetary Research

Role in the project: Planetary physics, formation and evolution of planetary systems, physics and chemistry of comets and asteroids, thermal properties of planetary bodies

Current Position: Head of Department "Asteroids & Comets" since 1997

Former Position(s):

- 1982-1990 Position in planetary research at the Institute of Space Research, East-Berlin
- 1992-today Scientist at the Institute of Planetary Research, DLR, Berlin
- 1994 Sabbatical at the Max-Planck-Institute in Katlenburg-Lindau (fellowship of the Leopoldina-Academy)
- 2009 Sabbatical at International Space Science Institute (ISSI) in Bern funded by the Otto-Lilienthal award of DLR

Education: Ph.D. in solid state physics, Humboldt-University Berlin "summa cum laude" (1982)

Honors:

- 1983 Humboldt-Award of the Humboldt-University for my PhD thesis
- 1993 Leopoldina Research Award for young scientists
- 2000 German-Polish Innovation Award
- 2003 Innovation Award of DLR
- 2008 Otto-Lilienthal-Award of DLR
- 2012 Space Technology – Hall of Fame Award of US Space Foundation
- 2017 Europlanet Prize for "Public Engagement with Planetary Science"

Selected publications:

- **Kührt**, E. (1984). Temperature Profiles and Thermal Stresses in Cometary Nuclei. Icarus 60, 512.
- **Kührt**, E. and Keller, H.U. (1994). The Formation of Cometary Surface Crusts. Icarus 109, 121.
- **Kührt**, E. (2002). From Hale Bopp's Activity to Properties of its Nucleus. Earth, Moon&Planets 90, 61.
- De Niem, D.; **Kührt, E.;** Motschmann, U. (2007). Ejecta range: A simulation study of terrestrial impacts. PSS 50, 900.
- Davidsson and 48 coauthors, incl. **Kührt, E**. (2016): The primordial nucleus of comet 67P/Churyumov-Gerasimenko. A&A 592, A63.
- de Niem, D.; **Kührt, E**.; Hviid, S.; Davidsson, B. (2018). Low velocity collisions of porous planetesimals in the early solar system. Icarus 301, 196.

NAME, First Name: **MICHEL, Patrick**

Affiliation: Lagrange Laboratory, Université Côte d'Azur,Observatoire de la Côte d'Azur, CNRS

Role in the project: Small body physical properties and dynamics, simulations of small body collisions (fragmentation + reaccumulations), simulations of surface processes

Current position: Director of Research (Senior Researcher) at CNRS (National Center of Scientific Research)

Former Position(s): Chargé de Recherche (Assistant Researcher) at CNRS, 1999-2010; Post-Doc at Torino Observatory (Italy, ESA external fellowship), 1997-1999

Education: PhD in Astrophysics (with Honors), 1997; Master Degree in Astronomy and Imaging (with Honors), 1994; Engineering Diploma in Aeronautics and Space Techniques, 1993

Services in National and/or International Committees (last ones):

- Member of the Space Program Committee of the French space agency CNES
- President of the Near-Earth Object Working Group of the International Astronomical Union (IAU)
- Member of the Steering Committee of the International Asteroid Warning Network (IAWN)

Honors:

- Prize Paolo Farinella (international prize in planetary science), 2013
- Carl Sagan Medal of the Division of Planetary Science of the American Astronomical Society, 2012
- Prize Young Researcher of the French Society of Astronomy and Astrophysics (SF2A), 2006
- Invited Professor at the Institute of Space and Astronautical Science (ISAS) of the Japanese space agency (JAXA), 2005

Selected Publications:

- Schwartz, S.R, **Michel, P.**, Jutzi, M., Marchi, S., Zhang, Y., Richardson, D.C. 2018. Catastrophic disruption as the origin of bilobate comets. Nature Astronomy.
- Libourel, G., **Michel, P.**, Delbo, M., Guanino, C., Recio-Blanco, A., de Laverny, P., Zolensky, M.E., Krot, A.N. 2016. Search for Primitive Matter in the Solar System. Icarus 282, 375-379.
- **Michel, P.**, Jutzi, M., Richardson, D.C., Goodrich, C.A., Hartmann, W.K., O'Brien, D. 2014. Selective sampling during catastrophic disruption: Mapping the location of reaccumulated fragments in the original parent body. Planetary & Space Sci. 107, 24-28.
- Delbo, M., Libourel, G., Wilkerson, J., Murdoch, N., **Michel, P.**, Ramesh, K.T., Ganino, C., Verati, C., Marchi, S. 2014. Thermal fatigue as the origin of regolith on small asteroids. Nature 508, 233-236.
- **Michel, P.**, Benz, W. & Richardson, D.C. 2003. Fragmented parent bodies as the origin of asteroid families. Nature 421, 608-611 (+ Journal cover).
- **Michel, P.**, Benz, W., Tanga, P. & Richardson, D.C. 2001. Collisions and Gravitational Reaccumulation: Forming Asteroid Families and Satellites. Science 294, 1696-1700 (+Journal cover)

NAME, First Name: ***de NIEM, Detlef***

Affiliation: German Aerospace Center (DLR), Institute of Planetary Research

Role in the project: Impact simulation, probalistic methods for collisions, astrodynamics+trajectory design.

Current position: Member of scientific staff, group AK (Asteroids & Comets)

Former Position(s): Researcher, IKF (Inst f. Kosmosforschung. Akademie der Wissenschaften DDR, Berlin) (1983-1990), Res. Engineer for Mars 96 / Mars Express / SMART-1 mission analysis/design, DLR Oberpfaffenhofen/Berlin (1990-1998), Researcher at DLR Institut für Planetenforschung (1998-present), staff position. In group AK since 2008.

Education: PhD in Physics, at TU Braunschweig 2007; Master's Degree (Diploma) in Physics, at Humboldt University (East) Berlin 1983.

Selected Publications:

- **de Niem, D.**, Geppert, U., Wiebicke, H.-J. (1985) : Envelopes of Rapidly Rotating Neutron Stars, Astrophysics and Space Science vol. 110, no.2, p. 331-336.
- Halm, I., Jansen, F., **de Niem, D.** (1993) : Cosmic Antiprotons In the Diffusion Model. I-General Properties in Comparision with other Models. Astronomy and Astrophysics, vol.269, p.601-607.
- B. A. Ivanov, **D. de Niem**, G. Neukum (1997) Implementation of dynamic strength models into 2D and 3D hydrocodes: Int. J. Impact Engng., Vol. 20, p. 411-430.
- **de Niem, D.** (1998) : Low-Thrust Trajectory Optimization For Smart-1. ESOC Contract Rep. No. 13260/98/D/IM.
- **de Niem, D.**, Kührt, E., Motschmann, U. (2007): A Volume-of-Fluid Method for Simulation of Compressible Axisymmetric Flow, Computer Phys. Comm. Vol. 177, 170-190.
- **de Niem, D.**, Kührt, E., Motschmann, U. (2008): Initial Condensate Composition during Asteroid Impacts. Icarus 196 Vol. 2, 539-551.
- **de Niem, D.**, Kührt, E., Morbidelli, A., Motschmann, U. (2012): Atmospheric Erosion and Replenishment induced by Impacts upon the Earth and Mars during a Heavy Bombardment. Icarus 221 Vol. 2, 495-507.
- **de Niem, D.**, Kührt, E., Hviid, S., Davidsson, B. (2018): Low Velocity Collisions of Porous Planetesimals in the Early Solar System . Icarus 301 Vol. 2, 196-218.

NAME, First Name: **OKLAY, Nilda**

Affiliation: German Aerospace Center (DLR) Institute of Planetary Research

Role in the project: Impact simulations of the defined scenarios using iSALE hydrocode.

Current position: Postdoc in the Geo-X framework

Former Position(s): Postdoc at the Max Planck Institute for Solar System Research (Göttingen, Germany)

Education: PhD in Physics from Georg-August-Universität Göttingen (2011), Master degree in Astronomy and Space Sciences (2006)

Services in National and/or International Committees (last ones): Reviewer for Icarus

Honors:

- ESA Award for 'Outstanding contribution to the ESA Rosetta mission'.
- A&A, v586 journal cover.
- Geo.X Young Academy postdoc grant.

Selected Publications:

- **Oklay N.**, Mottola, S., Vincent J.-B., and the OSIRIS Team, Long-term survival of surface
- water ice on comet 67P, MNRAS, 2017, 469, 582-597
- **Oklay N.**, Sunshine J. M., Pajola M., and the OSIRIS Team, Comparative study of water
- ice exposures on cometary nuclei using multispectral imaging data, 2016, MNRAS, 462,
- 394-414
- **Oklay N.**, Vincent J.-B., Fornasier S., and the OSIRIS team, Variegation of comet
- 67P/Churyumov-Gerasimenko in the regions showing activity, A&A ***(cover page)***, 2016,
- 586, A80
- **Oklay N.**, Vincent J.-B., Sierks H., and the OSIRIS team, Characterization of OSIRIS NAC filters for the interpretation of multispectral data of comet 67P/Churyumov Gerasimenko,A&A Rosetta special issue, 2015, 583, A45
- Vincent J.-B., **Oklay N.**, Pajola M., and the OSIRIS team, Are fractured cliffs the source
- of cometary dust jets ? insights from OSIRIS/Rosetta at 67P, 2016, A&A, 587, A14
- Vincent J.-B., **Oklay N.**, Marchi S., Höfner S., Sierks H., Craters on comets, 2015, PSS, 107, 53-63
- Turini D, Combe J.-P., McCord T. B., **Oklay N.**, Vincent J.-B, Prettyman T. H., McSween H. Y., Consolmagno SJ G. J., De Sanctis M. C., Le Corre L., Longobardo A., Palomba E.,Russell C. T., The contamination of the surface of Vesta by impacts and the delivery of the dark material, Icarus, 2014, 240, 86-102

NAME, First Name: **PENASA, Luca**

Affiliation: Centro di Ateneo di Studi e Attività Spaziali "Giuseppe Colombo" – CISAS, Via Venezia 15, 35131 Padova

Role in the project: investigation of morphological features observed on 67P and their potential relation to impacts.

Current position: post-doctoral researcher since 2016

Education: Phd in Earth Sciences 2015, previously Mater Degree in Earth Science (2011)

Selected Publications:

- **Penasa L.**, Massironi M, Naletto G, Simioni E, Ferrari S, Pajola M, et al. A three-dimensional modelling of the layered structure of comet 67P/Churyumov-Gerasimenko. Monthly Notices of the Royal Astronomical Society. 2017 Jul 21;469(Suppl_2):S741–54.

- Giacomini L, Massironi M, El-Maarry MR, **Penasa L.**, Pajola M, Thomas N, et al. Geologic mapping of the Comet 67P/Churyumov–Gerasimenko's Northern hemisphere. Monthly Notices of the Royal Astronomical Society. 2016 Nov 16;462(Suppl 1):S352–67.

- Lee J-C, Massironi M, Ip W-H, Giacomini L, Ferrari S, **Penasa L.**, et al. Geomorphological mapping of comet 67P/Churyumov–Gerasimenko's Southern hemisphere. Monthly Notices of the Royal Astronomical Society. 2016 Nov;462(Suppl_1):S573–92.

- Lucchetti A, Pajola M, Fornasier S, Mottola S, **Penasa L.**, Jorda L, et al. Geomorphological and spectrophotometric analysis of Seth's circular niches on comet 67P/Churyumov–Gerasimenko using OSIRIS images. Monthly Notices of the Royal Astronomical Society. 2017 Jul;469(Suppl_2):S238–51.

NAME, First Name: **WÜNNEMANN, Kai**

Affiliation: Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science (MfN) & Freie Universität Berlin, Institute of Geological Sciences, Planetary Sciences and Remote Sensing (FUB)

Role in the project: Impact cratering on planetary surfaces, asteroids and comets, numerical modeling of impact processes Core-developer of the shock physics code iSALE

Current position: Head of department "Impact and Meteorite Research" at MfN since 2009, Deputy head of science program "Evolution and Geoprocesses" at MfN, Professor for Impact and Planetary Physics at the MfN & FUB

Former Position(s):

- 11/2005-12/2008 Head of DFG Junior Research Group MfN
- 02/2004-06/2005 Fellow of German Research Foundation (DFG) and Research Associate at Lunar and Planetary Institute, University of Arizona, Tucson USA
- 01/2003-12/2003 Fellow of German Research Foundation (DFG) at Department of Earth Science and Engineering, Imperial College London, UK
- 03/2001-12/2002 Research Associate, Institute of Geophysics, WWU, Germany

Education: Diploma in Geophysics (1997) WWU Münster, Dr. rer. nat. (2001) WWU Münster

Services in National and/or International Committees (last ones): Convener, Meteoritical Society Meeting, Berlin, 2016; Chair, Co-Chair, Member, Program Committee MetSoc in Berlin (2016) and Mosow (2018), Santa Fe (2017)

Honors: Möbius-Award for distinct scientific achievements, 2010

Selected Publications:

- Prieur, N. C., Rolf T., Luther R., **Wünnemann K**., Xiao Z., Werner S. C. (2017), The effect of target properties on transient crater scaling for simple craters, J. Geophys. Res. Planets, 122, 1704–1726.
- Luther R., Artemieva N., Ivanova M., Lorenz C., **Wünnemann K**. (2017), Snow carrots after the Chelyabinsk event and model implications for highly porous solar system objects, Meteoritics and Planetary Science 52, 979-999.
- Rolf T., Zhu M.-H., **Wünnemann K.**, Werner S.C., (2016), The role of impact bombardment history in lunar evolution, Icarus 286, 138-152.
- **Wünnemann K.**, Zhu Meng-Hua, Stöffler D. (2016), Impacts into Quartz Sand: Crater Formation, Shock Metamorphism, and Ejecta Distribution in Laboratory Experiments and Numerical Models, Meteoritics & Planetary Science, 51, 1762-1794.
- Marchi S., Bottke W.F., Cohen B.A., **Wünnemann K.**, et al. (2013), High-velocity collisions from the lunar cataclysm recorded in asteroidal meteorites, Nature Geoscience,
- **Wünnemann K.**, Collins G. S., Melosh H. J. (2006): A strain-based porosity model for use in hydrocode simulations of impacts and implications for transient-crater growth in porous targets, Icarus 180, 514-527.