Research Networking Programmes

Science Meeting – Scientific Report

The scientific report (WORD or PDF file - maximum of seven A4 pages) should be submitted online within two months of the event. It will be published on the ESF website.

***Proposal Title**: Solar System Science with Gaia (S^3Gaia)*

***Application Reference N°:** 5379*

1) Summary (up to one page)

Gaia will perform a systematic astrometric and photometric survey of the whole sky down to magnitude V = 20 mag. The detected objects include some 300,000 small solar-system objects, which is more than 50 % of the known population of asteroids and comets. Gaia will directly measure sizes for about 1,000 objects, estimate the masses for 100 objects, derive spin properties and overall shapes of more than 10,000 objects, and yield much improved orbits and taxonomic classification for most of the observed objects. Low activity distant comets and Atira asteroids may also be discovered.

Given the above expectations, we organize a follow-up workshop to the Solar System Science Before and After Gaia -workshop (Pisa, Italy, 4–6 May, 2011) aimed at informing the scientific community active in asteroid and comet science about the unprecedented opportunities offered by the Gaia mission. The goal of S^3Gaia is twofold: on one hand to spread information and awareness about Gaia; on the other hand, to organize future activities and collaboration, in order to best exploit the observations that Gaia will perform.

Organizing S^3Gaia at the end of June 2014, some 3 months after the start of the scientific operations, allows predictions to be made about the actual end-of-mission data quality. In addition, organizing the workshop in connection with the ACM 2014 meeting ensures maximum visibility for the workshop within the international small-body community, and hence increases the likelihood for novel ideas for the exploitation of the Gaia data.

2) Description of the scientific content of and discussions at the event (up to four pages)

The S^3Gaia event at the ACM conference started with the invited plenary lectures by the Gaia Project Scientist Timo Prusti and the Gaia DPAC CU4 Co-Chair Paolo Tanga. Timo Prusti gave an overview of the entire Gaia mission and linked the mission to Solar System Objects (SSOs). Most SSOs to be observed by Gaia are asteroids and other small bodies, such as cometary nuclei. Paolo Tanga focused on the significance of the Gaia mission, first, for the determination of orbits and masses for asteroids with precise astrometry, and, second, for the physical characterization of asteroids from the precise photometry and astrometry to be provided by Gaia. The physical characterization will comprise the derivation of accurate masses for more than one hundred asteroids, rotation periods, pole orientations, and preliminary shape models for tens of thousands of asteroids, and spectral characterization for several hundreds of thousands of asteroids.

The first afternoon session of S^3Gaia was chaired by Timo Prusti and Alberto Cellino and focused on the orbital characteristics of SSOs to be observed by Gaia. Francois Mignard and Jean-Marc Petit presented the challenging problem of identifying moving objects from the data stream received from Gaia, followed by an assessment of linking the moving objects to known SSOs. Aldo Dell'Oro focused on special CCD processing needed for SSOs, on top of the processing applied to all objects in the data stream. Karri Muinonen and his colleagues presented the current MCMC-powered initial orbital-inversion method (Markov chain Monte Carlo) that is implemented in the Gaia DPAC CU4 short-term data-processing chain. In the ultimate implementation, MCMC is utilized to efficiently map the orbital-element phase-space domain within a pre-defined chi-square bound. A particular advantage of the implementation is the fact that it does not get stuck in local extrema, which is an important requirement in initial orbital inversion.

Dmitrii Vavilov and Yurii Medvedev offered a fast method for the estimation of impact probability of near-Earth objects. Indeed, the method was estimated to be orders of magnitude faster, when evaluating the preliminary impact probability, than the existing methods. Clearly, the further development of the method requires additional elaborations and detailed comparisons to existing methods. William Thuillot and his colleagues presented, in detail, the ground-based follow-up network Gaia-FUN for SSOs. There are more than 40 observatories involved in the effort. For SSOs discovered by Gaia, the follow-up task was shown to be extremely challenging due to the parallax (Gaia-based vs. ground-based observations) and due to the short observational time intervals available from the Gaia data. It turns out that, for such short time intervals, challenges remain almost independently of the astrometric precision of the data, something that is characteristic for the initial orbital-inversion problem.

Thomas Albin and his colleagues offered new algorithmic ideas for maximizing the detection of near-Earth objects. Whereas it is probable that these ideas cannot be implemented in the Gaia data-processing pipeline, they can be important for future pipelines. Vacheslav Emel'yanenko considered the role of near-Sun objects in determining the population of Chelyabinsk-type bodies and tied the topic to Gaia, which is, contrary to ground-based observatories, capable of observing near-Sun objects at small solar elongations. Such objects were shown to be particularly dangerous from the impact hazard point of view. Hans Rickman and his colleagues offered a mind-opening view to new cometary science stemming from the vastly improved knowledge of the Solar System neighborhood in the Milky Way, resulting from the Gaia mission. For example, Gaia will have a significant effect on our assessment of the cometary

component in the impact hazard due to small Solar System objects. Gaia will also observe cometary nuclei among the numerous asteroids to be observed. Piotr A. Dybczyński and Małgorzata Królikowska continued on the cometary studies by Gaia and drilled into the details of the apparent source of long-period comets.

The second afternoon session was chaired by Michael Mumma and Mirel Birlan and focused on the long-term dynamical and physical modeling of single asteroids as well as asteroid systems composed of several bodies. Daniel Hestroffer showed the prospects of Gaia, in particular, for binary asteroids. He presented an MCMC-based method for the orbital solution of the binary system using astrometric observations, a problem of utmost importance for the Gaia mission. Eva Schunova and her colleagues described the properties and evolution of near-Earth-object families created by tidal disruption at the Earth. Gaia will have a unique opportunity to discover such families among the NEOs residing close to the Sun. Thereafter, in the second session, case studies followed for individual objects for which Gaia will be offering additional observational data considered to be of importance. Peter Scheirich and his colleagues offered the state-of-the-art shape and rotation modeling for (99942) Apophis, a near-Earth object that continues to pose a future terrestrial impact threat. Sean Marshall continued with the shape model and thermal properties for the near-Earth asteroid (137032) 1998 UO_1 and Agata Rozek and her colleagues gave a spin-state and thermophysical analysis of the near-Earth asteroid (8567) 1996 HW_1. For these three objects, the forecoming Gaia astrometry and photometry will, first, provide a major improvement in the orbital accuracy, second, will provide complementary data for the shape and spin analysis, and, third, will help assess how the thermophysical characteristics of the surfaces couple with the orbital and rotational dynamics through the Yarkovsky and YORP effects. For accurate impact probability computations, as well as potential mitigation measures, all these characteristics need to be fully and quantitatively understood.

The third afternoon session was chaired by Naomi Murdoch and Petr Pravec and the session concentrated on the physical characterization of SSOs with the help of the Gaia data. Alberto Cellino described how the extensive photometric and spectroscopic data are completely revolutionary in their character: we will receive large numbers of observations and we will obtain a homogeneous view of the entire known population of SSOs, that is, several hundreds of thousands of objects. He then described how the photometric observations are utilized for the derivation of rotation periods, pole orientations, and preliminary shape models based on triaxial ellipsoids. Toni Santana-Ros and his colleagues continued with the preliminary shape modeling for observations combined from the Gaia and groundbased photometry. Thereafter, Josef Durech showed how the analysis of the rotational periods, poles, and shapes is carried out using the state-of-the-art convex inversion methods (where the shape are assumed convex), utilizing both Gaia and groundbased photometric data. We can expect tens of thousands of convex asteroid models based on all the existing photometric data on asteroids. Yurij Krugly and his colleagues described results of the near-Earth-asteroid photometry by ASPIN, an observing program that is particularly promising insofar as photometric Gaia follow-up observations are concerned. The third session and the entire S^3Gaia event ended with the presentation by Padma Yanamandra-Fisher on the role of amateur astronomers and social media in support of observing campaigns, in particular, in support of the Gaia mission. It is indeed striking how significant the amateur contribution is within the ground-based Gaia FUN activity.

3) Assessment of the results and impact of the event on the future directions of the field (up to two pages)

The S^3Gaia discussions described in the previous section are simultaneously indicators of future directions in the SSO research using the forecoming Gaia observations. Nevertheless, there are numerous research directions being initiated and/or strengthened by the S^3Gaia event. First, reliable identification of moving objects from the Gaia data stream, although having its roots in the past several centuries of SSO research, requires the development of new computational methods that utilize, on top of SSO motion, potential additional discriminators. What such discriminators are remains as an open problem. Second, the Gaia SSO Short-Term processing chain is the first processing chain that routinely utilizes Monte Carlo methods in initial orbital inversion. Whereas the current computational efficiency is sufficient for the expected SSO discoveries, improved efficiency would be needed for the application of the chain to all SSOs observed. Such an improvement could be achieved via massive parallelization of the computations, that is, an improvement that requires further method development.

Third, novel variants of MCMC inverse methods have been developed to tackle the Gaia SSO initial orbital inversion problem and the Gaia SSO binary system orbital inversion problem. There is great potential in extending these new methods into other inverse problems in the context of the Gaia mission. Ultimately, the global inverse problem concerning, simultaneously, all SSOs and all Gaia observational data, could be assessed using statistical methods further developed from the current MCMC methods utilized. This future research direction can extend to inverse problems outside the area of the Gaia mission, with cross-disciplinary significance.

Fourth, Gaia will offer important insight into the thermophysical Yarkovsky and YORP effects affecting, respectively, the orbital and rotational dynamics of SSOs. Whereas there is solid evidence for the Yarkovsky effect, the YORP effect has turned out to be extremely complex to tackle, for example, for asteroid systems composed of multiple bodies. Having the S^3Gaia event as part of the Asteroids, Comets, Meteors –conference has here been particularly beneficial, as it has become evident at the conference that the diffuse reflection of sunlight from random rough asteroid surfaces can cause lightcurve effects that mix with the signal from the YORP effect. Further studies are called for to assess, quantitatively, the significance of the YORP spin-up/spin-down and the significance of lightcurve phase shifts due to multiple scattering of light in the particulate surfaces of asteroids.

Fifth, it is evident that the MCMC inverse methods described above will soon find their counterparts in the photometric inversion of Gaia data for the rotation and shape characteristics of SSOs. This will remove a long-term deficiency in asteroid lightcurve inversion methods: a rigorous, statistical treatment for rotation and shape parameters has been missing for more than a decade.

Finally, the homogeneous observational data by the Gaia mission will allow unprecedented SSO population studies to be performed. Most probably, along the lines presented at the S^3Gaia event and at the ACM conference at large, the near-Earth-object population model will be utterly revised in the post-Gaia era. In the main belt of asteroids, population models for asteroid families will be thoroughly revised. The S^3Gaia event has been a major driver for future research on small SSOs.

Annex 4a: Programme of the meeting

Thursday, July 3rd

Plenary session, chairs: Faith Vilas and Peter Jenniskens

- **Timo Prusti**, Gaia
- **Paolo Tanga**, Gaia as a Solar System observatory

Session I, chairs: Timo Prusti and Alberto Cellino

- **Francois Mignard** and Jean-Marc Petit, Detection and recognition of moving objects with Gaia
- **Aldo Dell'Oro**, Procedures, challenges, and expectations of the astrometry of asteroids with Gaia
- **Karri Muinonen**, Hanna Pentikäinen, Mikael Granvik, Dagmara Oszkiewicz, and Jenni Virtanen, Asteroid orbital inversion using uniform phase-space sampling
- **Dmitrii Vavilov** and Yurii Medvedev, Fast method for the estimation of impact probability of near-Earth objects
- **William Thuillot**, Benoit Carry, Jerome Berthier, Pedro David, Hadrien Devillepoix, and Daniel Hestroffer, Ground-based follow-up of Solar System objects detected by Gaia
- **Thomas Albin**, Sonja Albrecht, Detlef Koschny, and Gerhard Drolshagen, Maximizing the detection of near-Earth objects
- **Vacheslav Emel'yanenko**, The role of near-Sun objects in determining the population of Chelyabinsk-type bodies
- **Hans Rickman**, Marc Fouchard, Christiane Froeschle, and Giovanni B. Valsecchi, Using Gaia for cometary science
- **Piotr A. Dybczyński** and Małgorzata Królikowska, Towards a better understanding of the apparent source of long period comets

Session II, chairs: Michael Mumma and Mirel Birlan

- **Daniel Hestroffer**, Dynamics of single and multiple asteroids based on Gaia observations
- **Eva Schunova**, Kevin J. Walsh, Mikael Granvik, Robert Jedicke, Richard J. Wainscoat, and Nader Haghighipour, Properties and evolution of near-Earth-object families created by tidal disruption at the Earth
- **Peter Scheirich**, Petr Pravec, Josef Durech, Joe Pollock, Peter Kusnirak, Kamil Hornoch, Adrian Galad, Emmanuel Jehin, Jean Manfroid, Cyrielle Opitom, Michael Gillon, Francois Colas, Julian Oey, Jan Vrastil, Daniel Reichart, Kevin Ivarsen, Joshua Haislip, and Aaron LaCluyze, The shape and rotation of the tumbling asteroid (99942) Apophis
- **Sean E. Marshall**, Ellen S. Howell, Michael C. Nolan, Christopher Magri, Donald B. Campbell, Lance A. M. Benner, Patrick A. Taylor, Alessondra Springmann, Peter G. Brown, Petr Pravec, Yanga R. Fernandez, Ronald J. Vervack Jr., Marina Brozovic, Michael W. Busch, Jon D. Giorgini, and Steven J. Ostro, Near-Earth asteroid (137032) 1998 UO1: Shape model and thermal properties
- **Agata Rozek**, Stephen C. Lowry, Benjamin Rozitis, Stephen Wolters, Michael D. Hicks, Samuel R. Duddy, Alan Fitzsimmons, Simon Green, Colin Snodgrass, and Paul Weissman, Spin-state and thermophysical analysis of the near-Earth asteroid (8567) 1996 HW1

Session III, chairs: Naomi Murdoch and Petr Pravec

- **Alberto Cellino**, The expected Gaia revolution in asteroid science: Photometry and spectroscopy
- **Toni Santana-Ros**, Przemyslaw Bartczak, Tadeusz Michalowski, Paolo Tanga, and Alberto Cellino, Testing the inversion of the Gaia asteroid photometry combined with groundbased observations
- **Josef Durech**, Asteroid spins and shapes by combining Gaia and ground-based observations
- **Yurij Krugly**, Igor Molotov, Raguli Inasaridze, Otar Kvaratskhelia, Vova Aivazyan, Vasilij Rumyantsev, Irina Belskaya, Alexandr Golubaev, Alexey Sergeev, Vasilij Shevchenko, Ivan Slyusarev, Otabek Burkhonov, Shuhrat Ehgamberdiev, Leonid Elenin, Victor Voropaev, Vladimir Koupianov, Ninel Gaftonyuk, Alexander Baransky, Tatiana Irsmambetova, Elena Litvinenko, Abbas Aliev, and Tungalag Namkhai, Results of near-Earth-asteroid photometry in the frame of the ASPIN programme
- **Padma A. Yanamandra-Fisher**, Role of amateur astronomers and social media in support of observing campaigns

Annex 4b: Full list of speakers and participants

The “Solar System Science with Gaia” was organized in conjunction with the “Asteroids, Comets, Meteors 2014” conference. The full conference had 461 participants from 41 countries. Below we list only the speakers in the “Solar System Science with Gaia”-workshop. The workshop was open for all the ACM participants, thus the number of participants was much larger than the number of speakers.

Workshop speakers:

Thomas Albin, Alberto Cellino, Aldo Dell'Oro, Josef Durech, Piotr A. Dybczynski, Vacheslav Emel'yanenko, Daniel Hestroffer, Yurij Krugly, Sean E. Marshall, Francois Mignard, Karri Muinonen, Timo Prusti, Hans Rickman, Agata Rozek, Toni Santana-Ros, Peter Scheirich, Eva Schunova, Paolo Tanga, William Thuillot, Dmitrii Vavilov, and Padma A. Yanamandra-Fisher

Session chairs (if not speakers):

Mirel Birlan, Peter Jenniskens, Michael Mumma, Naomi Murdoch, Petr Pravec, and Faith Vilas