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Report on the ESO Workshop

Diversis mundi: The Solar System in an Exoplanetary context (OPS-III)

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Inspired by the previous two Observing Planetary Systems (OPS) workshops held in ESO-Chile and by the rapid evolution of exoplanet studies and Solar System exploration, we organised the *Diversis Mundi* workshop. The focus of this conference was to bring together the Solar System and exoplanet communities to put the Solar System into the context of the current knowledge of planetary systems and to understand all the known components of extrasolar systems. Around 100 researchers from both communities met and discussed these topics in a very collaborative and inspiring environment, and in a workshop format that enhanced the interaction between the two communities.

Motivations

After centuries of wondering, we now know that planets abound in the Universe. Indeed, according to recent work based on results of the Kepler mission and ground-based surveys, at least one planet inhabits each FGKM star in our Milky Way. The exponential increase in the number of known extrasolar planets in the last 30 years has brought with it a variety of unexpected environments and architectures where planets can grow. The absence of these configurations in the Solar System (like the presence of super-Earths or hot Jupiters) is still puzzling and shows that many factors influence the shaping of a planetary system, making them very different in structure and composition. However, the Solar System is one of the key pieces of this jigsaw puzzle. It is our test laboratory, a place where we can directly explore the result of the processes that give rise to the formation of an environment suitable to host life as we know it, and the only place where we can collect in-situ information (at least over human time scales). Moreover, the new results from the Solar System exploration probes in recent years have shown that our celestial home is still a mystery. Questions about how Earth became a water world, why Mars became a desert, what the origin is of the diverse orbital properties of Jupiter trojans or how moons are formed, are just some of the large crop of unknowns that remain open.

On the positive side, several instances of exocomets have been identified (for example, in β Pic) and since 1984, thanks to the InfraRed Astronomical Satellite (IRAS), we are also aware of Kuiper-belt-like structures around other stars and we are already looking for exomoons and exotrojans. This suggests that at least some of the components present in the Solar System are also present elsewhere as outgrowths of the planet formation process. In addition, the plethora of exoplanets found so far at different stages of their lives can provide a complete picture of how these bodies form and evolve, as well as external feedback to our theories of Solar System structure.

Exploring the synergies between the Solar System and exoplanet communities and investigating how each of these fields can feed or contrast the theories of the other is critical to understanding the big picture of planetary systems and to unveiling our own history. We proposed the *Diversis Mundi* (OPS-III) workshop — with the invaluable help of the exoplanet and Solar System experts from ESO, both in Chile and Garching — with the main motivation of bringing together researchers from both communities to discuss the current status of the two fields and build bridges to connect them. The workshop focussed on two main topics: (1) thinking about extrasolar systems as extra Solar Systems, with all their components, and (2) putting the Solar System in context with the wide variety of extrasolar system properties found so far.

In order to achieve these goals, we designed a workshop format specifically intended to merge both fields and to enhance the interaction between the two communities. We identified four main topics that are key to understanding the big puzzle of planetary systems: (a) the formation of planetary systems and their components; (b) the architecture and evolution of planetary systems; (c) small components of planetary systems; and (d) planetary atmospheres and biomarkers. The meeting was then divided into four sessions corresponding to these four main topics, with one day devoted to each. Finding the synergies between both communities in these four main areas is crucial to understanding our own environment and for the search for life outside the Solar System. Joining together people from both fields is an opportunity for them to learn, test their ideas, and trigger inter-disciplinary collaborations. The last day of the meeting was devoted to the "Present and future facilities for the exploration of planetary systems". The full programme and presentations are available online[1,2].

In order to succeed, a workshop aimed at two communities requires both a broad audience with expertise in the two fields, and a format designed to encourage interaction, discussion, and collaboration between them. To achieve these two key requirements, a particular effort was made in selecting the invited and contributed speakers, and in designing the format of the invited talks and the hands-on activities. We chose to have a one-hour session each day to open the topic with a broad view of the theme, chaired by an international expert from each community in what we called "bridge talks". Total freedom was given to the two speakers in designing their combined talk to encourage their interaction before the conference. An invited talk focussed on a particularly relevant topic was scheduled after the lunch break on each day. This kept the focus of the session and encouraged digging into a particular science case. The schedule was filled with contributed talks on the topic of the day. At the end of each day, sessions with different goals were organised. In particular, in the Tuesday session we organised round tables on seven big topics where the audience from both communities split to discuss and bring up new ideas. A "blackboard session" to present short results with only the support of chalk was organised on Thursday afternoon. Finally, a poster session was scheduled on Thursday to give an opportunity to the poster presenters to explain their work and leave some time for free discussion.

In the coming paragraphs, we present summaries of some particularly interesting talks and highlights from each session.

Figure 1. Conference photo at the ESO premises in Vitacura.

Formation of planetary systems and their components

The bridge talk of the first session of the workshop was given by Jürgen Blum & Joan Najita, who discussed the formation of planetesimals and planets. They summarised our understanding of planetesimals and planet formation, from the evolution of dust in protoplanetary discs, to pathways towards planetesimals, and finally planet formation. They also discussed what we can learn about planet formation from the observations of discs using mainly ground-based facilities.

The other talks of that session were mainly dedicated to the study of protoplanetary discs. The use of new facilities/instruments has revealed a whole diversity of features (for example, gaps, vortices, rings, asymmetries) in young planetary discs and revolutionised our view of their structure. Findings from large surveys of discs with ALMA were presented by, amongst others, François Ménard, Laura Pérez and Nienke van der Marel. Several results from observations of proto-planetary discs with the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) were presented too. Even though a planet forming inside a disc has not been directly observed yet, such observations are essential to constrain planet formation models.

Architecture and evolution of planetary systems

The first talk of this session was again a bridge talk, this time focussed on the dynamical evolution and architecture of Solar and extrasolar systems. Aurélien Crida and Pedro Figueira discussed the link between planet formation and evolution mechanisms and the observed demographics of exoplanets as well as the structure of the Solar System. They reviewed how mechanisms such as core accretion, gravitational instability, and planet migration shape planetary systems, and how those can be linked to the observed structure of our own Solar System and the diversity of exoplanet systems we have observed so far.

Very interesting contributions about various aspects of the architecture and evolution of planetary systems followed this bridge talk. The results of a survey aimed at detecting Solar System twins was presented by Jorge Meléndez, who showed that such systems might be very rare. Later, Dino Mesa and Alice Zurlo presented the first results from the SpHere INfrared survey for Exoplanets (SHINE), the purpose of which is to provide the best statistical constraints to date on the population of giant exoplanets. Solar System architecture and evolution were not left out of the discussion, and an invited talk by Matija Çuk in the afternoon was devoted to theories of the formation of the Moon, and highlighted the necessity of moving on from the Giant Impact theory. A lot of work still needs to be done before reaching a clear picture on how planetary systems, including our own, evolve.

Small components of planetary systems

This session started with a bridge talk on water in small bodies of the Solar System and in planetary systems in the formation stage. In the first part of the talk, Karen Meech reviewed what we know about water in our Solar System, and how evidence of water-driven activity is found in unexpected places, such as the main asteroid belt. Studying the isotopic signature of water, in combination with other chemical fingerprints, is key to establishing connections with early stages of planet formation, and understanding how, when, and from where Earth got its large water content. In the second part of the talk, Edwin Bergin made the link between the history of water in the Solar System and our current understanding of how the water is formed and transported from clouds to discs, and to planetesimals. Observations with the space-based telescopes Spitzer and Herschel allow the emission of water molecules to be traced, from before stellar birth to the disc stage. This in turn allows the initial conditions of water distribution (as gas and ice) available at the time of planet formation to be established.

During the rest of this session, several talks were devoted to the detection of small bodies outside the Solar System. Alex Teachey presented an overview of the search for exomoons in Kepler data and the latest updates about the exomoon candidate Kepler-1625b I. Isabel Rebollido-Vázquez and Daniela Iglesias discussed the search for exocomets, and Siyi Xu the study of a transiting extrasolar asteroid. Even though we have now begun detecting small bodies in extrasolar systems, we still do not fully understand the origin and formation of small bodies in our own system. In the afternoon, Silvia Protopapa gave a summary of the results of the New Horizons mission, which flew by Pluto in July 2015, allowing us to gather critical information on the surface composition, geology, and atmosphere of Pluto and its satellites.

Planetary atmospheres and biomarkers

The bridge talk of this fourth session was given by Patrick Irwin and Nikole Lewis and was focussed on the atmospheres of giant planets in the Solar System and beyond. In the past 40 years, our understanding of the composition, structure, atmospheric circulation, photochemistry, and cloud formation in the atmospheres of the Solar System giant planets has markedly improved, thanks to a combination of several space missions and ground-based observations. However, numerous questions still remain, despite the ability to study those planets in much more detail than is possible for exoplanets. Much progress has been made during the past 10 years in observation techniques and methodologies as well as in specialised atmospheric and circulation models, many of which have their roots in Solar System studies. This has allowed us to begin probing the atmospheres of exoplanets, especially those of hot Jupiters, which are extremely different from what we observe in Solar System planets.

Later that day, Elyar Sedaghati and Monika Lendl presented very interesting results from transmission spectroscopy of the atmospheres of hot Jupiters using the FOcal Reducer/low dispersion Spectrograph (FORS2) on the Very Large Telescope (VLT). Among these was the first discovery of a metal oxide in the atmosphere of an exoplanet by Sedaghati and collaborators. In the afternoon, Máté Ádámkovics presented an overview of the dense, nitrogen-dominated atmosphere of Titan, which could serve as an example for exoplanet atmospheres with haze and clouds.

Present and future facilities for the exploration of planetary systems

The first talk of the last session was given by Bin Yang and Claudio Melo, on behalf of Luca Pasquini, presenting the variety of ESO instruments used to study Solar System objects, planets in extrasolar systems, and protoplanetary discs. The emphasis was on second-generation instruments such as the Multi Unit Spectroscopic Explorer (MUSE), SPHERE and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), and the new capabilities that will soon be available were presented. This was followed by John Carpenter who discussed the wide range of planetary science observations that can be performed with the Atacama Large Millimeter/submillimeter Array (ALMA). Finally, the last talk of the conference was about the James Webb Space Telescope (JWST), and its capabilities to observe Solar System objects and exoplanets.

In addition to the five regular sessions, round-table sessions provided an excellent environment for more detailed discussions about critical open questions regarding planetary systems and their formation. As an example, one of the round tables, chaired by Jürgen Blum, was devoted to discussing the formation of planetesimals. During this round table, the need to develop new ways to test the different planetesimal formation models was emphasised. Those would concern both the Solar System small body population, and the structure and composition of protoplanetary discs outside the Solar System. In any case, the visit to the Kuiper belt object 2014 MU69 by the New Horizon mission in late 2018 could provide an essential test for planetesimal formation models. Another round table was chaired by Karen Meech and dedicated to the interstellar interloper `Oumuamua. The first part of the discussion focussed on what additional observations could have been made if the observability of the target had been better, and what further properties could be investigated for the next interstellar object detected crossing the Solar System, such as making a size estimate. The strange shape of `Oumuamua and the implications for its formation mechanism were also discussed.

This third Observing Planetary Systems workshop was a real success, thanks to a combination of a careful choice of invited speakers and the specific format of the workshop. It allowed the synergies between the Solar System and exoplanet communities to be explored, and numerous ideas were exchanged and discussions started. The bridge talks, featuring two speakers discussing complementary subjects from each community, were particularly fruitful and the blackboard presentation proved a very efficient means to present short scientific results to a wide audience. Gathering the Solar System and exoplanet communities

together to foster and encourage collaboration is essential to reaching a better understanding of the structure, formation, and evolution of exoplanetary systems as well as why the Solar System is so peculiar and how life appeared on Earth. Such workshops are of great value in ensuring progress in that direction. We hope that future OPS workshops, as well as others in this area, continue to promote collaborations between the two communities.

Demographics

For a workshop that covered two areas with the main aim of building bridges between them and that was held in Chile (far from the usual European or US venues but in a country where astronomy is growing fast), the selection of the invited speakers and contributed talks was crucial to attracting researchers from all over the globe and from the two communities. To that end, we composed a Scientific Organising Committee (SOC) with the following criteria: world-wide expertise in their field; gender balance; topic balance; and origin balance. The final SOC was composed of: Jorge Lillo-Box (ESO, co-chair); Cyrielle Opitiom (ESO, co-chair); Monika Lendl (Austrian Academy of Sciences); Eric Ford (PennState); Nuria Huélamo (Astrobiology Center, CAB); David Kipping (Columbia University;, Christophe Mordasini (Bern University); Colin Snodgrass (The Open University); Karen Meech (University of Hawai'i); Imke de Patter (University of California); and Emmanuel Lellouch (LESIA, Observatoire de Paris). This included six men and five women, with five experts in different exoplanet fields and their five counterparts in Solar System studies, plus one expert in planetary system dynamics (with influence in both communities). Seven of them were from European institutions and four from US institutions.

The ESO proposing team presented a proposal for the workshop format, previously discussed in internal meetings, focussed on bridging the two communities. This proposal was discussed by the SOC and some modifications were introduced to accommodate the different suggestions. The SOC proposed a list of invited speakers, focusing on researchers with broad topic knowledge for the bridge talks. In the end 57% of the invited speakers were from the Solar System community and 43% from the exoplanet community (with a 56:44 male:female ratio). The submitted contributed talks were split into four panels matching the four topics of the conference. The expert from each field then gave a score to each abstract and the final decision was taken based on their scores by the two chairs of the workshop. We received 58 abstracts, of which 40 could be scheduled. The male:female ratio of the submitted abstracts was 60:40, as was the ratio of scheduled talks. Interestingly, we found a clear gender imbalance per topic: while men submitted many more abstracts for planet formation and evolution topics (the first two sessions of the workshop) leading to a 68:32 male:female ratio, women submitted more abstracts for the small components and atmospheres topics, with a 40:60 male:female ratio. Regarding the two broad communities, however, the imbalance was very strong, with 28% of the talks related to the Solar System and 72% related to exoplanet studies.

As to the participants, we hosted 95 attendees during the week, filling the venue. The male:female ratio was 67:33, proportional to the ratio of submitted abstracts although still far from gender balanced. This highlights once more the still unequal scientific society and showing that much more needs to be done, at a higher level, in this regard. We had a reasonably balanced participation from the different stages of the scientific career: 36% of attendees were PhD students, 28% postdocs and 36% tenured/senior astronomers. These percentages were also broadly reflected among the speakers and poster presentations. The attendees came from four continents with the following distribution: South America (49%); Europe (33%); North and Central America (17%, including Mexico, US and Canada); and Asia (1%). The lack of attendees from Africa (sadly typical of international conferences held in Europe and America) also points to the challenges of doing science in this continent and the relative lack of resources, another challenge to our goal of a modern and global scientific society.

In summary, the *Diversis Mundi* workshop hosted a wide variety of expertise within the two main topics of the conference and brought together people from many different nationalities and backgrounds. The high level of participation with a full conference room on all five days of the workshop demonstrated the interest in this kind of mixed workshop.

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Links

[1] Link to the workshop programme: http://www.eso.org/sci/meetings/2018/ops2018/program.html
[2] Presentations are available via Zenodo: https://www.zenodo.org/communities/diversismundi2018