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RESEARCH CONFERENCES

ESF-FWF Conference in Partnership with LFUI

Putting our Solar System in Context: Origin, Dynamical and Physical Evolution of Multiple Planet Systems

Universitätszentrum Obergurgl (Ötz Valley, near Innsbruck) • Austria
25 - 30 April 2010

Chair: **Dr. Mario G. Lattanzi,** INAF, Osservatorio Astronomico di Torino, IT
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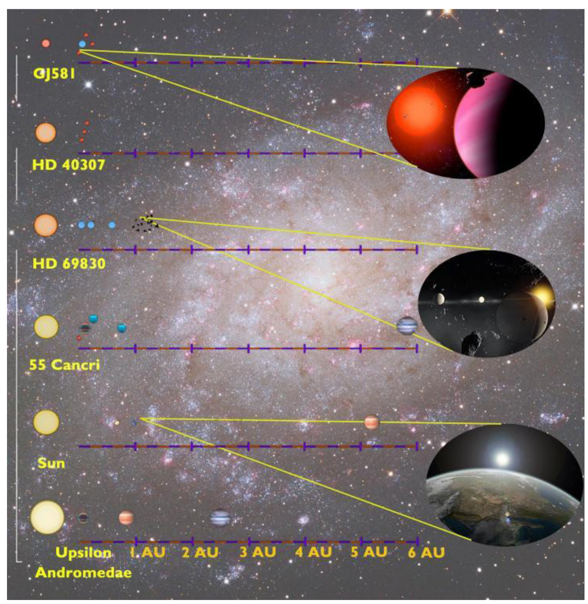

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Conference Highlights

Please provide a brief summary of the conference and its highlights in non-specialist terms (especially for highly technical subjects) for communication and publicity purposes. (ca. 400-500 words)

The discovery and characterization of planets orbiting other stars is one of the newest and fastest growing fields in modern astronomy. Hundreds of exoplanets have been discovered over the past 15 years, accurate masses and radii (and therefore bulk densities) have been determined for dozens, and in several cases the planetary atmospheres have been studied spectroscopically, yielding temperatures, chemical compositions, and even information about the weather. In contrast, detailed characterization of the planets in our own solar system has a long history, albeit with many recent advances. The aim of this conference was to bring the two communities together so that they could learn from each other, and good progress was made towards this goal. On the one hand, the planets in our solar system are understood in considerable detail because they are nearby and have been studied up close, and this understanding can help guide people who model exoplanets. On the other hand, exoplanets show a stunning diversity of architectures, and this diversity provides new insights to people who model the formation and evolution of the solar system.

The conference was organized in three thematic sessions. Session 1, which occupied the first day of the conference, focused on the state-of-the-art of observations of planetary systems obtained with a variety of techniques (radial velocity, transits, direct imaging, astrometry), and also discussed future observing programs, both from the ground and in space. Session 2, which lasted the whole of the second day, focused on the interpretation of the observations from the standpoint of the dynamical evolution of N-body systems (multiple-planet systems and planets in multiple stellar systems), including our own Solar System. The last two days of the conference were dedicated to Session 3, which focused on current theoretical explanations provided for the observational material in terms of possible scenarios for the formation, physical evolution, and habitability of planetary systems, with the ultimate goal of putting our Solar System in context.

This conference schedule achieved the broad aims of 1) summarizing the current understanding of this very rapidly evolving, highly interdisciplinary field; 2) presenting the latest ideas, models, techniques, and observations; 3) fostering the interaction of the Solar-System science and astronomical communities; 4) identifying crucial objectives and problems that will enable clear, coherent advancement of the field in the coming years.

Young scientists were encouraged to present their results through contributed poster presentation sessions (with presenters having three-minutes for summarizing the contents of their posters), and a number of them were selected for short oral presentations (15 minutes).

Upon conclusion of the conference, a vibrant ‘Forward Look Discussion’ was carried out, during which future developments in the field, both theoretical and observational, were debated. The final discussion aimed at fostering fruitful interactions between the solar-system science and exoplanet astrophysics communities.

X I hereby authorize ESF – and the conference partners to use the information contained in the above section on ‘Conference Highlights’ in their communication on the scheme.

Scientific Report

Executive Summary

(2 pages max)

The study of exoplanets orbiting solar-type stars has emerged in the last decade to be one of the most exciting new areas of astronomy and planetary science. Since 1995, almost 500 planets outside the solar system have been discovered, mostly by the radial-velocity method (a technique that can only put lower limits on the mass of any detected companion). Collectively, they span a huge range of masses and orbital distances, have been found around most stellar types, and have led to major revisions in our ideas of how and where planets form and what their structure is. The majority of these planets are gas giants, but more than 70 are of Neptune mass and lower. Ninety-seven (four of which in multiple-planet systems) are known to transit across the disk of their primary star, and it is for these that we have physical parameters such as radius and mass. A subset of the close-in transiting giants has now been detected directly at secondary eclipse and at various orbital phases by the Spitzer Infrared Space Telescope and the Hubble Space Telescope, providing the first measurements of extrasolar planetary atmospheres and compositions. To interpret these data, theorists have developed models for planet formation, orbital interaction and dynamics, evaporation due to stellar irradiation, atmospheric circulation and global heat transport, atmospheric structure and spectra, phase light curves, the equations of state of their interiors, molecular chemistry, radius evolution, and tidal effects, to name only a few topics.

The first exoplanetary system known to comprise multiple planets orbiting a normal star was the triple system υ And, detected by the radial velocity method just four years after the first confirmed exoplanet 51 Peg b. The subsequent discovery of a second planet orbiting 47 UMa and the resonant pair of planets orbiting GJ 876 foreshadowed the discovery of almost four dozen more systems. Today, 17% of known host stars of exoplanets within 200 pc of the Sun are known to be multiple-planet systems, and another 15% show significant evidence of multiplicity in the form of long term radial velocity trends. The recent proliferation of multiple-planet systems is due to the increase in both the velocity precision and duration of the major planet search programs. The increased time baseline has led to the detection of long-period outer companions. Today, the 10+year baseline of high precision (< 5 m/s rms) radial velocity planet searches means that most planets with a < 3 AU now have multiple complete orbits observed, improving their detectability. Even planets with a > 4 AU which have not yet completed a single orbit can sometimes have well-constrained masses and periods, as in the case of HD 187123 c. Radial velocity precision has steadily improved toward 1 m/s with the HIRES spectrograph at the Keck Observatory (Hawaii) and with the HARPS spectrograph at La Silla Observatory (Chile). This has allowed the detection of ever-weaker signals, and correspondingly lower-mass planets, and led to the discovery of some of the lowest-mass planets known in multiple systems, including (among others): 55 Cnc e, GJ 876 d, the triple system of Neptune-mass planets around HD 69830, μ Ara d, the triplet of 'Super-Earths' discovered orbiting HD 40307, and the recently discovered 7-planet system orbiting HD 10180 with masses in the Neptune/Super-Earth regime.

The evidence so far gathered provides clues to a set of very interesting, and somewhat puzzling, properties of planetary systems. Multiple-planet systems show great diversity from the standpoint of long-term dynamical evolution, with at least three main families easily identifiable: a) hierarchical systems, in which secular/resonant gravitational interactions are negligible and their orbits can be very well approximated as independent Keplerian trajectories, b) secularly interacting systems, in which long-term significant variations of the orbital elements can be inferred by means of numerical integrations of the equations of motion, and c) systems in stable mean motion resonances, that can undergo variations of the orbital elements on timescales comparable to the time-span of the radial-velocity data (the planets b and c in the GJ 876 system being the most outstanding example). Furthermore, planetary systems appear to have different orbital elements distribution functions with respect to those of single-planet systems, particularly for what concerns their eccentricities. In addition, orbital elements and mass distributions for low-mass systems (containing Neptunes and Super-Earths) may also differ from those of systems containing gas giants. Finally, there are hints (albeit with the present-day small-number statistics) that the planetary frequency may also be a different function of the host's mass and its metal content in single- and multiple-planet systems.

Multiple-planet systems constitute ideal laboratories to search for fossil evidence of formation, orbital migration, and dynamical evolution processes. Their emerging properties in the near future may be put on much more solid statistical grounds, thanks to an going and soon to become larger flow of observational data collected with a variety of techniques which help answer some of the most outstanding question in this branch of planetary science, such as: 1) How many families are there from a dynamical point of view? 2) What are the true masses of planets in multiple systems? 3) Are their orbits coplanar, as in our Solar System, or do they exhibit large relative inclination angles? 4) What is the origin of their eccentricities? 5) Do their distribution functions and frequencies differ from those of single-planet systems? The present-day standard models accepted to describe the formation of planetary systems within a circum-stellar disk (the so-called 'core-accretion' scenario), the various attempts at explaining how systems of planets can migrate inward or outward within a disk during formation, and the many venues investigated to characterize their long-term dynamical evolution are far from providing a sensible, global picture, and more data are crucially needed to help distinguish between proposed models.

The near future holds bright promises to do just so. Radial-velocity surveys from the ground are both extending the time baseline of the observations and are now probing orbital distances in the 3-7 AU range, as well lowering the limiting measurement precision, allowing for detection of companions with minimum masses as small as a few times the mass of the Earth at short orbital distances (< 0.3 AU). Both from the ground and in space, the prospects of transit photometry are particularly bright, with the tantalizing possibility of determining the radius of planets as small as the Earth in the region of habitability of solar-type stars as well as infer the existence of additional planets, respectively, thanks in particular to the exquisite photometric as well as timing precision of the currently operating CoRoT and Kepler missions.

For systems in which more than one planet is found to be transiting, their densities will be determined solely based on photometric data, thus allowing to probe models of planetary internal structure in multiple systems (we recall that as of today no planet found transiting its parent star is known to be in a multiple-component system). High-precision astrometric measurements carried out from the ground (VLTI/PRIMA) and in space (Gaia) will allow to resolve the mass ambiguity intrinsic to radial-velocity data and will determine the actual relative alignment between pairs of planetary orbits for most of nearby (d < 200 pc) planetary systems. Many significant new results in this sub-field of planetary science are expected within the next couple of years, which will indeed fuel significant theoretical efforts.

The ESF Conference "Putting Our Solar System in Context" constituted an excellent venue for discussing the origin, dynamical, and physical evolution of multiple-planet systems by confronting the latest observational findings with new theoretical developments in the field. The conference, whose program and main scientific highlights are outlined below, achieved the broad aims of 1) summarizing the current understanding of this very rapidly evolving, highly interdisciplinary field; 2) presenting the latest ideas, models, techniques, and observations; 3) fostering the interaction of the Solar-System science and astronomical communities; 4) identifying crucial objectives and problems that will enable clear, coherent advancement of the field in the coming years.

Young scientists were encouraged to present their results through poster presentation sessions (with presenters given three-minutes for summarizing the contents of their posters) and a number of them were selected for short oral presentations (15 minutes).
Upon conclusion of the conference, a vibrant ‘Forward Look Discussion’ was carried out, during which future developments in the field, both theoretically and observationally, were debated. The final discussion aimed at fostering fruitful interactions between the solar-system science and exoplanet astrophysics communities. This crucial step is highly desirable, as to date exoplanet research has been driven by astronomers, while planetary scientists have by and large focused largely on our solar system. However, the expertise and accumulated wisdom in planetary science is vast, and the merger of its perspectives and knowledge with the new astronomical discoveries being made outside the solar system will greatly enrich both.

Scientific Content of the Conference

(1 page min.)

- *Summary of the conference sessions focusing on the scientific highlights*
- *Assessment of the results and their potential impact on future research or applications*

SESSION 1: THE PRESENT, AND FUTURE PROSPECTS

Session 1, which occupied the first day of the conference, focused on the state-of-the-art of observations of multiple-planet systems obtained with a variety of techniques (radial velocity, transits, direct imaging, astrometry), and also discussed future observing programs, both from the ground and in space. Most notable highlights included a) in-depth statistical analyses (J. Wright) of the significant reservoir of multiple systems (a rather common occurrence, including the first long-period giant planets on orbits similar to that of our Jupiter), and their impact on models of orbital migration and dynamical evolution, b) ambitious attempts (M. Endl) at detecting Earth-like planets around the nearest stars to our Sun, c) detailed studies (J. Steffen) of the potential of the transit timing variation (TTV) technique to detect outer planets in systems in which one is found transiting its parent star, d) pioneering studies (D. Kipping) of how a combination of techniques (transits, Rossiter-McLaughlin effect, transit timing and transit duration variations) could help to discover Earth-sized, possibly habitable moons of extrasolar giant planets, e) comprehensive analyses (Moro-Martin) of datasets on dusty debris disks, to begin understanding the connection between the presence of leftover material at large orbital radii (hundreds of astronomical units) from the central star and the existence of fully formed planets closer in (as is the case for our Solar System), and f) the identification of the actual role of several cutting-edge techniques, such as ground-based, high-resolution, high-contrast direct imaging (S. Desidera), space-borne, high-precision astrometry (M. Shao), and ultra-high precision transit photometry in space (D. Latham, H. Rauer), for the detection of single- and multiple-planet systems containing (possibly habitable) planets with masses as small as that of the Earth, and of the potential synergies between these techniques for the purpose of improved characterization of planetary systems.

SESSION 2: INTERACTIONS

Session 2, which lasted the whole of the second day, focused on the interpretation of the observations from the standpoint of the dynamical evolution of N-body systems (multiple-planet systems and planets in multiple stellar systems), including our own Solar System. Most notable highlights included a) detailed analyses (D. Fabrycky) of how tidal dissipation can affect the migration, dynamical configuration, tidal heating, and transit variation signature of planets in multi-body systems, b) studies of Hot Jupiters dynamics (D. Queloz) through the statistics of spin-orbit angle measurements in transiting systems, c) investigations of how the early stages of dynamical interaction between the outer Solar System planets (A. Morbidelli) can provide clues for improved understanding of the great diversity of extrasolar systems, d) detailed dynamical studies of the inner and outer Solar System asteroid belts (A. Cellino, R. Malhotra), looking for fossil evidence of the early stages of the dynamical evolution of our Solar System, and e) improved modeling of the early orbital evolution of planetary systems (W. Kley) in the context of orbital migration models for both resonant (A. Crida) and non-resonant (Y. Miguel) planetary system architectures.

SESSION 3: FORMATION, STRUCTURE, AND HABITABILITY

Session 3, which occupied the third and fourth day of the conference, focused on the theoretical explanations provided for the observational material in terms of the possible scenarios for the formation, physical evolution, and habitability of planetary systems, with the ultimate goal of putting our Solar System in context. Most notable highlights included a) new developments (Y. Alibert) in our understanding of the formation mechanism(s) of Jupiter, Saturn, and extrasolar giant planets, b) further insights (S. Raymond) on the formation scenario for the Solar System terrestrial planets, and beyond, c) theoretical predictions on the formation of and evaluation of the prospects (N. Haghighipour) for the detection of habitable Super-Earths around low-mass stars in the near future, d) improved modeling of the compositional diversity of massive extrasolar planets, in relation to the internal structure of the Solar System giants (M. Havel), e) new predictions on the interiors and plate tectonics of massive terrestrial planets in relation to our Earth (D. Valencia), f) analyses of the atmospheric evolution of Venus, Earth, Mars and Moons of our Solar System (H. Lammer), and the implications for terrestrial exoplanet characterization, g) state-of-the-art overviews of the steps to take in order to be able to read a terrestrial planet's spectral fingerprint and characterize if it is potentially habitable (L. Kaltenegger), and h) space-borne experiments aimed at characterizing biochemically the surface and underground of the planet nearest to our Earth, Mars, in search for elementary forms of life (A. Blanco).

Forward Look

(1 page min.)

- *Assessment of the results*
- *Contribution to the future direction of the field – identification of issues in the 5-10 years & timeframe*
- *Identification of emerging topics*

An impressive group of experts was enlisted to present invited talks on a well-chosen and balanced selection of topics. The invited talks were uniformly of high quality and they were supplemented by a suite of appropriate contributed talks and posters. The main results mentioned above were of high scientific standards. The final discussion aimed at fostering fruitful interactions between the solar-system science and exoplanet astrophysics communities. Only time will tell whether planetary scientists and extrasolar planet experts have been brought closer.

During the forward look session, future developments in the field, both theoretical and observational, were debated. On the observational side, to go beyond the state-of-the-art instrumentation, the development of ultra-high precision spectrographs both at visible and infrared wavelengths was discussed, particularly those to be installed on the next generation of 30-40 meter telescope, which will become operational by the end of the decade. The development of There were good interactions between top scientists from NASA and ESA missions, with informal discussions of plans for possible joint missions towards the end of the decade. On the theoretical side, several key open issue were identified as far as formation, internal structure, and orbital evolution of planetary systems are concerned. As a particular example, the study of the structural properties (including the existence or not of significant plate tectonics) and atmospheric dynamics of Super-Earths, planets with a range of masses not found in our Solar System, was identified as a topic of crucial importance to be addressed within the next 3-5 years.

Among the many relevant emerging topics, the rich dynamical portraits of systems with close-in planets was identified as a matter of particular interest, thanks to the variety of detailed measurements carried out for transiting systems. The possibility of publishing some of the key conference results in a special issue of Advances in Space Research is under consideration.

▪ Is there a need for a foresight-type initiative?

Not at this time.

Atmosphere and Infrastructure

▪ *The reaction of the participants to the location and the organization, including networking, and any other relevant comments*

It was common perception that the first two days of the conference were very full, with the sessions continuing after dinner. The third and fourth days were less demanding. However, the participants reacted very positively. Most of them considered the scheduled presentations at the ‘cutting edge’ of science, clearly defining and analysing the most important problems and opportunities in the field. The speakers’ presentations were mostly considered as well delivered, often conducive to vibrant discussions. Most of the participants found that formal discussions, often evoking and exploring new research directions, were sufficiently stimulated by the session Chairmen, with enough time devoted to them, although at times they appeared dominated by only a few individuals and did not involve the whole group. The majority also considered the poster session a useful addition, providing significant scientific input to the meeting. According to the participants, the conference aims were timely, clearly and efficiently communicated, and in the end fully realised, ultimately making for a very successful conference. Virtually everyone felt that the conference should be repeated.

As for atmosphere/networking activities, most considered the conference more than "just a meeting", or a collection of lectures. All participants took all their meals together, and this encouraged casual interactions. Coffee breaks in the mornings and afternoons also provided opportunities for informal interactions, although the coffee break area was often quite busy. Overall, it was common feeling that the schedule might have allowed for more time for informal discussions. The bar was a popular venue for decompression after the day’s schedule was accomplished. Thanks to the remarkable influx of young people drawn to the field of exoplanets by the many opportunities for new ideas and research projects, the median age of the participants was unusually young. The vast majority agreed that the organizers succeeded in their efforts to get good participation by experts from both sides of the Atlantic, in making opportunities for young newcomers from Europe to participate, in achieving a representative balance of all national groups, and in reaching an appropriate balance between young and senior participants.

The conference organization and management was rated good to excellent by virtually everyone, with efficient administration of the facility and a very professional job done by the on-site ESF manager. The site in the Tyrol Alps was spectacular, and the excursion to a mountain refuge overlooking glacier areas very much appreciated. The food service was mostly considered reliable, its quality/quantity being disputed by few. The facility was clean, and the presence of an on-site gym noted positively by many. The internet service was considered basically good, although wireless service went down in the main rooms on two days, and some of the bedrooms had no internet access.

Sensitive and Confidential Information
This report will be submitted to the relevant ESF Standing Committees for review.
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Date & Author:

25/08/2010 **Mario G. Lattanzi & Alessandro Sozzetti**