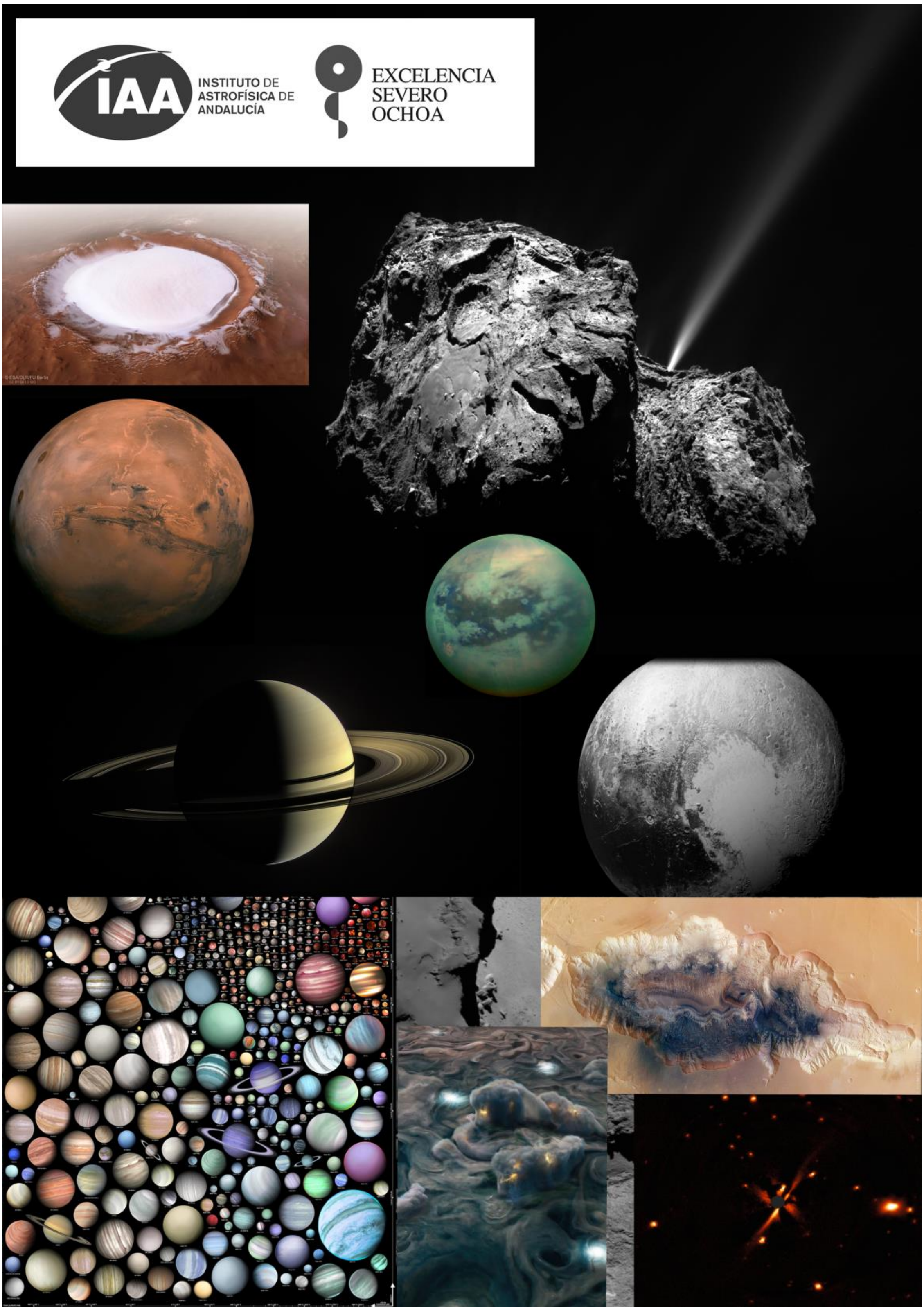
MINISTERIO DE CIENCIA E INNOVACIÓN

EXCELENCIA SEVERO OCHOA 01-07-2018 A 30-06-2022

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA (IAA)



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Planets, exoplanets and their systems in a broad and multidisciplinary context

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Introduction

The school aims at providing a comprehensive understanding of the planetary systems in a broad context such that the current knowledge about exoplanetary systems and solar system can be viewed in a common frame.

The lectures cover topics related to protoplanetary discs, the host star, rocky planets, habitability, fluid and icy giants, satellites, atmosphere including clouds and escape, minor bodies and debris discs.

The lessons are specially addressed to Master and PhD students, young Post-Docs.

Origin and evolution of the planetary systems

"A brief outline of Solar System history" by Alessandro Morbidelli (Observatoire de la Cote d'Azur, Nice, France)

I will summarize the most important observational constraints that guide the models attempting to reconstruct the history of the Solar System. Then I will discuss the main models concerning giant planet formation and migration in the protoplanetary disk, terrestrial planet accretion and the final dynamical reorganization of the structure of the solar system via a phase of dynamical instability of the giant planets occurring after the removal of gas from the protoplanetary disk.

"From disk to planetary systems: end-to-end models and population synthesis" by Yann Alibert (Center for Space and Habitability, University of Bern, Switzerland)

I will present short recapitulation on the core instability model. End-to-end models of planetary system formation will be outlined. Finally, a comparison with extrasolar planets will be done and the case of the solar system will be analysed in the frame of the contents of this lecture.

"The compositional dimension of planet formation" by Diego Turrini (Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy)

Many physical processes governing planet formation canstill be studied only indirectly. The composition of planetary bodies, however, holds a number of clues that we can use to gain insight on them. In this lecture, I will show how, from the meteorites in the Solar System to the giant planets around the Sun and other stars, from the circumstellar disks surrounding newly formed stars to the polluted atmospheres of white dwarfs, composition provides a window into the similarities and differences in the formation history of planets and their planetary systems.

"Planet formation: from protoplanetary disk observations to theories" by Zhaohuan Zhu (University of Nevada, USA).

Recent high angular resolution observations towards protoplanetary disks (e.g. from ALMA, VLT and ground based observations) have revealed unprecedented details on the planet forming region. These observations provide us direct clues on the planet formation processes. In this lecture, I will summarize the latest observations, and how these observations have changed our understanding of planet formation. I will emphasize the importance of connecting observations and theory for advancing the research field.

"Planet Forming Disks in the ALMA era" by Luis Zapata (Institute of Radio Astronomy and Astrophysics National Autonomous University of Mexico, Mexico)

In this talk, I will review the latest advances on planet formation using submillimeter observations with The Atacama Large Millimeter/Submillimter Array (ALMA). Despite the detection of close to 4100 fully formed planets, there are only a handful of planets detected during their formative stages. Towards these forming planets ALMA observations have revealed a variety of substructure in continuum emission from protoplanetary disks suggestive of planet–disk interactions sculpting the dust density distributions. These disk structures include rings, gaps, and holes within these planets in formation. Surprisingly analysis of the gas kinematics of these disks together with theoretical modeling have suggested the presence of gas accretion flows in the vicinity of young planets. Finally, I will also talk about the efforts to detect complex molecules in disks that can help to understand the chemical complexity observed in mature planets as the Earth.

The host star

"The mercurial Sun at the heart of our solar system" by Phil Judge (University Corporation for Atmospheric Research, USA)

As the powerhouse of our solar system, the Sun's planetary influences appear contradictory. On the one hand, the Sun for aeons was "just right" for life to evolve in our terrestrial Goldilocks zone, even for such complex organisms as ourselves. On the other hand, in the dawn of Earth's existence the Sun was far dimmer than today, yet evidence for early liquid water is written into geology. Now in middle age, according to most astronomers, it should be a benign object of little interest. Yet, it not only floods the planets with near-constant light and heat, but for elementary physical processes yet to be fully understood,it contains a magnetic machine for converting some of the Sun's power into fast-changing high energy particles, photons and magnetic fields. With an arrhythmic 11 year heartbeat and regular high energy eruptions, we will discuss some physical reasons why the Sun suffers from such ailments, and examine consequences through time across the solar system

"Twenty-five years of exoplanetary systems discoveries, what we have learned so far?" by Bárbara Rojas Ayala (Universidad de Tarapacá, Chile)

For centuries, humanity wondered if there were other worlds like ours in the Universe. For about a quarter of a century, we have known that planetary systems exist around other stars with the discovery of 51 Peg b, and the more than 3000 exoplanetary systems discovered so far since 1995. But, what we have learned from these discoveries? In this lecture, I will address the characteristics of the stellar hosts, the kind of planets that can be found around nearby stars according to their characteristics, the biases and the empirical correlations that have been found around stars with and without planets, and how these discoveries have challenged what we thought about our own solar system.

Rocky planets

"Telluric planets: comparative planetology" by Ann Carine Vandaele (Planetary Aeronomy Division at Institut d'Aeronomie Spatiale de Belgique, Belgium)

The planets of our Solar System have been scrutinized, and still are, by various space missions which provide a wealth of information on their surfaces and atmospheres. Studying Solar System bodies and in particular the terrestrial ones, will provide us valuable information to better understand their evolution, and eventually their habitability. Comparative planetology aims at a global understanding of the processes existing on planets or planet-like bodies, through the observation of physical phenomena acting under a wide range of conditions (pressure and temperature, magnetic field etc.) and forcing (distance to the Sun, for example). I will describe the terrestrial planets and review some of the most recent space missions having visited them. We will consider some examples to illustrate the concept of comparative planetology.

“Atmospheres and climates of telluric planets of the solar system” by Aymeric Spiga (Sorbonne Université, Faculté des Sciences and Laboratoire de Météorologie Dynamique, Paris, France)

A fleet of spacecraft visited Mars, Venus and Titan -- Saturn's moon, but arguably a quasi-planet, unveiling fascinating climates and atmospheric phenomena. We will discuss in this lecture interesting examples of physical, dynamical and chemical processes illustrating the current research challenges on terrestrial planets' atmospheres, not only on observations but also on modeling. A related question would be paleoclimates and whether current knowledge and models can be used as time capsules. Possible parallels with Earth's, giant planets' and exoplanets' atmospheres will be opened. This lecture will be incredibly, almost scandalously, inexhaustive and we will only present a drop in the ocean -- yet hopefully this drop would excite curiosity to further explore this ocean of knowledge.

“The history of water on Mars through its geomorphology - clues to the climate and evolution of Mars as a planet” by Susan Conway (Université de Nantes, Nantes, France)

I will talk about the evidence for water on Mars recorded by its surface and how these geomorphological clues have been used by researchers to infer the amounts of liquid water at the surface of Mars over its history. I will discuss the debate regarding whether early Mars was warm and wet, or cold and wet. I will also talk about how landscapes and landforms on Mars have lead to vigorous debates about the presence or absence of liquid water today and in the recent past.

“What the Observed Mass-Radius Relation of Small Exoplanets is telling us about their interiors and atmospheres” by Mercedes López-Morales (Center for Astrophysics | Harvard & Smithsonian, Massachusetts, USA)

Transit and radial velocity techniques have now reached the level of precision necessary to accurately measure masses and radii of small exoplanets (sub-neptunes, super-earths, and rocky planets) around nearby stars. We have already measured masses and radii of over 30 small planets, and with those numbers in hand some patterns about the physical and chemical properties of those planets are starting to unveil. In this lecture, I will describe how masses and radii of those small planets are being measured to those precision levels. I will also describe what we have now learned from the measurements we have so far and where this topic is heading next.

“Planetary systems with rocky exoplanets and the search for exoplanet atmosphere biosignature gases” by Sara Seager (Massachusetts Institute of Technology, Massachusetts, USA)

Thousands of exoplanets are known to orbit nearby stars and small rocky planets are established to be common. There is furthermore a growing list of nearby stars with rocky exoplanets, contributing to the momentum to the future study of rocky exoplanet atmospheres. The eventual goal is to detect a gas that might be indicative of life. A suitable “biosignature gas” is not just one that might be produced by life, but one that: can accumulate in an atmosphere against atmospheric radicals and other sinks; has strong atmospheric spectral features; and has limited abiological false positives. Which gases might be potential biosignature gases in a yet unknown range of rocky exoplanetary atmospheres? New computer simulations and next-generation telescopes coming online means the ambitious goal of searching for "biosignature gases" in a rocky exoplanet atmosphere is within reach.

"Habitability and atmospheric biosignatures in an exoplanetary context" by Lee Grenfell (German Aerospace Center and Technical University, Berlin, Germany)

The extent of habitable conditions beyond the Solar System and the potential range of atmospheric biosignatures are central issues in exoplanetary science. We are currently at a fascinating juncture where characterization of specific objects such as Proxima Centauri-b and the TRAPPIST-1 planets are emerging themes for favoured targets that lie in, or close to, the habitable zone. It is the task of a new generation of atmospheric models to determine the climate and atmospheric compositions of these fascinating objects. In this lecture, I will review the factors affecting planetary habitability and discuss the various definitions of the habitable zone. I will also provide a brief overview of exoplanetary atmospheric biosignatures and their spectral signals. Finally, I will discuss some relevant recent literature highlights in this rapidly developing field.

Fluid and icy giants: the planet and its system

"Unveiling Jupiter with Juno: Consequences for Giant Planets" by Tristan Guillot (Observatoire de la Cote d'Azur, Nice, France)

- Formation of giant planets: basics.

- Constraints on Jupiter's interior structure.

- The deep winds of Jupiter (and Saturn).

- Structure and Role of the atmosphere.

- Towards icy giants and giant exoplanets.

"Exploration of the Gas Giants: Jupiter and Saturn" by Leigh Fletcher (University of Leicester, Leicester, United Kingdom)

In the first decades of the 21st century, our understanding of the Giant Planets has been revolutionised by detailed orbital exploration (the Juno mission to Jupiter and the Cassini mission to Saturn) and Earth-based observation. This talk will summarise some of our latest discoveries at Jupiter and Saturn, including new insights into their banded structure (the belts and zones), the depth of the winds, and their interiors. We will discuss their composition; implications for thermochemistry, photochemistry, and cloud-formation; and the vertical temperature structure and its connection to atmospheric circulation. Furthermore, we'll explore what our Giant Planets can teach us about exoplanets and Brown Dwarfs, and suggest some tantalising questions for future planetary exploration.

"The Ice Giants Uranus and Neptune: current data and future exploration" by Ricardo Hueso (Universidad del País Vasco, Bilbao, Spain)

Uranus and Neptune are giant planets formed by rock and ice forming elements covered by hydrogen and helium atmospheres that comprise about a 15-20% of their masses. These atmospheres have high abundances of volatiles (methane, hydrogen sulphide, ammonia and water) and both factors make these planets essentially different to the Gas giants Jupiter and Saturn. The Voyager 2 flybys of Uranus and Neptune in 1986 and 1989 respectively were key steps to learn about these "ice" planets and opened many questions that are still unanswered about their chemical composition, inner heat sources and deep structure and nature of convection in the observable clouds. Ground-based observations, modern analysis of the Voyager data and continuous work on planet formation processes keep improving our understanding of these planets, and major sources of information will come from new telescopes such as JWST and ELT. However, we lack essential data related to their vertical structure, atmospheric dynamics and complex magnetospheres that only a space mission can provide. New mission concepts to explore Uranus and Neptune are being developed and could be a reality in the 2040s. The similarities of our close Ice giants with the very large fraction of exoplanets with similar masses currently known make such a close characterization a major point of interest in modern planetary sciences.

"Tenuous atmospheres of the Solar System" by Emmanuel Lellouch (LESIA, Observatoire de Paris-Meudon, France)

While Mars is often regarded as the prototype of a thin atmosphere, no less than a dozen planetary-sized Solar System bodies have been found to harbour even more tenuous atmospheres, with a broad range of pressure and composition, and a diversity of origins, including surface sputtering, (cryo)volcanism and sublimation equilibrium. Current knowledge of this tenuous will be reviewed, with emphasis on the collisionnally-thick atmospheres of Pluto, Triton, and Io. We will discuss the properties of these atmospheres in terms of surface-atmosphere exchanges and pressure evolution, atmospheric composition and chemistry, thermal structure, energy budget and escape.

"Exoplanets from super Earths to sub-Neptunes and gas giants: demographics, atmospheres" by Kevin Heng (Center for Space and Habitability, University of Bern, Switzerland)

Transit and radial velocity detections have uncovered a broad diversity of exoplanet types ranging from super Earths (with radii slightly larger than that of Earth) to sub-Neptunes (with radii twice to thrice that of Earth) and gas giants (with Jupiter-like sizes), typically found in orbital configurations unlike that of our Solar System. Observations with the Hubble Space Telescope and various ground-based telescopes are starting to reveal the chemical compositions of their atmospheres, even though this effort is still in its infancy. In this lecture, I will review the state of the art of the observations of exoplanetary atmospheres and the methods used to interpret them. Sub-Neptunes are of particular interest, as they are potentially in a regime intermediate between the primary, hydrogen-dominated atmospheres of the gas giants and the secondary, outgassed atmospheres of the terrestrial exoplanets. For secondary atmospheres, developing an understanding of the magma-atmosphere interactions and geochemical cycles shaping them is key. Upcoming observatories such as the James Webb Space Telescope, ARIEL and the Extremely Large Telescope should decisively advance our knowledge on the chemical diversity of sub-Neptunes.

"The role of clouds in exoplanet atmospheres" by Hannah Wakeford (University of Bristol, Bristol, United Kingdom)

Every planet, dwarf planet, or moon in our solar system with a stable atmosphere has clouds. Clouds (solid or liquid droplets suspended in a gas), control the energy budget of an atmosphere, how much light is reflected, absorbed, and trapped. To understand the physics and chemistry of a planetary atmosphere we need to measure the amount, composition, and ratio of the main gas components, but the ever-present clouds can have a significant impact on the atmosphere's chemistry and dynamics. As exoplanets have been discovered, investigations of their atmospheres quickly revealed that they also have clouds reflecting, absorbing, scattering, and trapping their stars light. In the optical to near-IR wavelength range, these clouds make it difficult to measure the abundance and composition of atmospheric gasses, but they can also indicate the presence of dynamical mixing and temperature structures, to which gas phase atmospheric chemistry is much less sensitive. I will talk about the exotic clouds that are present in exoplanet atmospheres and the observations we are making, and plan to make, to try and understand their role in exoplanet atmospheres. I will look at the physics of absorption, scattering, and reflection, and why we should not dismiss cloudy exoplanets when trying to understand their formation.

"The atmospheres and structure of Hot Jupiters" by Jonathan Fortney (University of California, Santa Cruz, USA)

I provide a brief review of many aspects of the planetary physics of hot Jupiters. I examine our current understanding of the evolutionary history and current interior structure of the planets. In particular I focus on viable models to explain the inflated radii of the population, based on the statistics of the exoplanet population. I discuss aspects of their atmospheres in the context of observations and 1D and 3D models, including atmospheric structure, spectroscopic signatures, and complex atmospheric circulation. The major opacity sources in these atmospheres are discussed and I will look to the future with JWST, ARIEL, and high-resolution ground-based spectroscopy.

"Theory and observational evidence of planet atmospheric escape" by Luca Fossati (Space Research Institute, Austrian Academy of Sciences, Graz, Austria)

The long-term evolution of a planetary atmosphere is predominantly shaped by escape, a process leading atmospheric gas to leave the planet's gravitational well and disperse into space. Escape is a fundamental process affecting planetary atmospheric structure, composition, and evolution. For example, within the solar system, escape is known to have shaped the early atmospheres of Venus, Earth, and Mars. The powerful atmospheric escape that affected these planets in the past no longer takes place in the solar system. However, it can be observed and studied on short-period exoplanets. I will review the theory of planet atmospheric escape, from Jeans escape to strong hydrodynamic outflow. I will further go through some of the most important non-thermal escape processes, which are those relevant for the current solar system planets. I will finally present the observational evidence currently available for the existence of atmospheric escape and how it is believed this process affects the observed exoplanet population.

Small bodies and debris disks

”Planetary astrophysics of small bodies” by David Jewitt (University of California Los Angeles, USA)

The so-called "small bodies" of the solar system are, on-average, less thermally-evolved than planets and other large objects. For this reason, many small bodies preserve primordial material and are some of the most important for understanding the origin and evolution of the solar system. I will discuss the nature and significance of small solar system bodies, focusing on new work concerning the asteroids, comets, Trojans, Centaurs, Kuiper belt objects and interstellar interlopers. I will take a big-picture view in order to illuminate some of the driving questions for which we presently have no answers.

"Physical properties of small bodies of the Solar System derived from remote observations and the problem of data x modelling." By Daniela Lazzaro (Observatorio Nacional, Rio de Janeiro, Brazil)

In recent years, it has become clear that the physical properties of the small Solar System bodies are extremely important in tracing not just their formation and evolution but also the major dynamical processes undergone by our planetary system. However, the relevant physical properties, such as diameter, shape, albedo, rotation state, surface roughness and composition, interior structure etc. are not observable. Thus, we must rely on the modelling of the data obtained through remote observations. In this presentation, we will discuss the main observables and how model-dependent are the derived physical properties.

"Using small solar system bodies (comets, asteroids) to help understand the formation of habitable worlds" by Karen Meech (Institute for Astrophysics, Hawaii University, USA)

Small primitive bodies can provide information about the solar system's formative processes, including the contribution of pre-solar and interstellar sources. Interstellar objects are thought to be planetesimal remnants that have been ejected out of their own solar system, and they can provide insight into the process of building exoplanetary systems. The most primitive Solar System objects are found beyond the asteroid belt. They have largely been undisturbed since their formation. Thus, their compositions provide a fossilized record of the chemical make-up of our planetary system during its origin. No one knows how water arrived at our planet, or whether our solar system, with a planet possessing the necessary ingredients for life within the habitable zone, is a cosmic rarity. We do not know the role that the gas giants played in delivering essential materials to the habitable zone. The answers to these questions are contained in unaltered primitive body volatiles. The most likely volatile delivery candidate came from the outer solar system. Evidence of what arrived at Earth is hard to determine from Earth materials because of the processing that has occurred. However, whatever was delivered to the inner solar system was also trapped in the asteroid belt where some of those primitive materials exist today. Studying accessible volatiles in the main belt, found in the main belt comets will provide some of the key information needed to understand the origins of these materials. However, in order to understand the formation of our planetary system we have to not only trace the early chemistry, but also understand the dynamical environment. A new class of objects, the Manx comets, may provide clues to allowing us to trace the dynamical history. This lecture will touch upon how many of these objects are discovered, what they can tell us about the early solar system, and what observations from the ground, from space and from in-situ missions will give us the information we need to learn about planetary system formation.

"Comets, clues to the early history of the Solar System" by Dominique Bockelée-Morvan (LESIA-Observatoire de Paris-Meudon, France)

Comets are the leftover building blocks of giant planet cores and other planetary bodies, and fingerprints of Solar System's formation processes. Their composition provides clues to the chemistry and conditions prevailing in the early Solar System. These objects have also preserved materials that predate the formation of the protoplanetary disk. This lecture will provide a broad overview of the properties of cometary nuclei and atmospheres, including new knowledge obtained from the Rosetta mission. The second part of the lecture will emphasize on the chemical properties of cometary ices and how do they compare with the composition of star-forming regions and protoplanetary disks.

"Chasing ice in the Solar System" by Noemí Pinilla (Florida Space Institute, USA)

Ice, in different forms, is present through the Solar System, from Mercury, the planet closest to the Sun, to the Oort Cloud, the vast reservoir of long-period comets. But the abundance of ice is predominant in the outskirts of the Solar System. In particular, beyond the gas giants, the population trans-Neptunian objects (TNOs) contain large amounts of the ice that condensed from the cloud that gave birth to our Solar System. This population, which was unknown 30 years ago and includes Pluto, formerly known as the ninth planet, constitutes the main reservoir of ice in the actual Solar System that is accessible for observers. Other small bodies, such as Trojans, Hildas, or some asteroids in the outer belt, which may have formed beyond the snow line, could also harbour ices beneath their surfaces. In this lecture, I will review the history and characteristics of these icy small bodies, and the observational evidence of the presence of ice. Special attention will be devoted to the largest and brightest members of this population, where Pluto, recently visited by the spacecraft New Horizons, will have its dedicated section. In the end, I will assign a special chapter to what future studies will be when the James Webb Space Telescope gives us access to the IR light from TNOs, unexplored territory for these small, cold, and distant bodies.

"Interstellar planetesimals" by Amaya Moro Martín (Space Telescope Science Institute, Baltimore, Maryland, USA)

Extensive surveys of extrasolar planets and of circumstellar disks around nearby stars show that planets and dust-producing planetesimals, similar to the asteroids, Kuiper belt objects and comets in our solar system, are ubiquitous around others stars. The planetesimal population of the young solar system was very numerous initially but the majority of the objects ended up ejected due to gravitational perturbations with the planets and other external perturbers. Numerical simulations indicate that many other planetary systems would have experienced a similar evolution, yielding to an interstellar space filled with ejected planetesimals. This is why, for decades, we had been puzzled that none of these interstellar planetesimals was ever detected crossing the solar system, even though it would have been easily identified as a hyperbolic comet. Then, when 1I/'Oumuamua, the first interstellar interloper, was finally discovered, our puzzlement grew into utter bewilderment. From its detection with PanSTARRS, and taking into account the depth and duration of this survey, we can infer how many 1I/'Oumuamua-like objects are out there and this number, we will see, is at least ten times larger than what one would be expected from the ejection of planetesimals from extrasolar planetary systems, leaving unanswered the question of its origin. Furthermore, even though we would expect most of the ejected planetesimals to be icy, because the majority would originate from the outer regions of their parent systems, 1I/'Oumuamua did not show evidence of any of the outgassing typical of solar system icy bodies, leaving unanswered the question of its composition. And, if that wasn't enough, there was no observational evidence that we could invoke outgassing to account for the non-gravitational acceleration found in its unbound orbit, leading to a dizzying range of proposed scenarios, including a giant snowflake formed in the outer region of an extrasolar planetary system, a devolatilized aggregate of loosely-bound dust grains resulting from the disintegration of an extrasolar comet, a hydrogen iceberg from a failed star, and even a solar-sail from an extra-terrestrial civilization.

Regardless of the origin and nature of 1I/'Oumuamua, the discovery of 2I/Borisov, the second interstellar interloper, with an unquestionable cometary composition, has reassured us that a population of icy interstellar planetesimals exists. Similar to their crossing of our solar system, these interstellar planetesimals will also enter the environments where planet formation is taking place. When we estimate the number of interstellar planetesimals that can be trapped in these environments, we find that the number expected to be incorporated to each star- and planet-forming disk can be very significant. The interest of these trapped planetesimals is that they could have sizes large enough to rapidly grow into larger bodies, via the direct accretion of the sub-cm sized dust grains in the protoplanetary disk, before the planetesimals drift toward the star due to gas drag, overcoming the meter-size barrier that challenges the growth of cm-sized pebbles into km-sized objects, an unsolved problem in planet formation theories. This suggests that the trapping of interstellar bodies in these environments should be considered in future planet formation models but require a better characterization of the population of interstellar planetesimals, particularly its background density, size, and velocity distributions.

"Planetesimal/debris discs" by Sebastian Marino (University of Cambridge, Cambridge, United Kingdom)

Planetary systems are not only composed of planets, but also of minor bodies similar to asteroids and comets which we typically found in belts analogous to the Asteroid and Kuiper belt in the Solar System. Although we cannot detect these bodies individually, mutual collisions between these km-sized *planetesimals* produce high dust levels that are readily detectable around 30% of nearby stars. These planetesimals form as a byproduct of planet formation, and their distribution is shaped by the presence of planets in the same way the Asteroid and the Kuiper belts were shaped by Jupiter and Neptune, respectively. Therefore planetesimal discs provide unique and complementary constraints on the architecture and dynamics of planetary systems. In this lecture, I will summarise how planetesimal/debris discs are studied today, with special focus on Kuiper belt analogues (or exoKuiper belts) to show how over the last few years we have been able to constrain their volatile composition, radial distribution, and interaction with known or unseen planets.

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