Handbook of Exoplanets

Hans J. Deeg • Juan Antonio Belmonte
Editors

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With 910 Figures and 107 Tables

Springer

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Foreword

In the search for other worlds, the last decades have probably been among the most exciting over the past centuries, possibly since the years of the Copernican heliocentrism and the discovery by Galileo of the Moons around Jupiter. The large series of breakthroughs in the search for exoworlds make this recent period a rather remarkable time in the history of astronomy which appears to be as fascinating as the one about 400 years ago when humankind started to abandon geocentrism.

During the past 25 years, we have witnessed the detection of planets orbiting thousands of nearby and distant stars. Since the discovery of the first planets around pulsars in the early 1990s and the first Jupiter-mass planet around the solar-type star 51 Peg in 1995, a large diversity of planetary systems, has been identified in the nearby universe. Efficient hunting programs have provided increasing statistical evidence that planets are very common around stars. More than 50% of the stars in our galaxy may host planetary systems and therefore, tens of billions may await discovery. The detection rate of exoplanets has only increased with time, reaching values above one exoplanet discovery per day. The number of known exoplanets, several thousand, will considerably increase in the coming decade thanks to the many search programs already started or planned for ground and space telescopes.

The study of this extremely rich population of planetary systems will lead to a better understanding of their architecture and the physics involved in the formation processes. Ultimately, the ongoing search and characterization work may unveil planets with adequate conditions to sustain the development of life and will pave the road to the discovery of exolife.

Planets with masses similar to those existing in the Solar System are frequently found in other planetary systems, displaying very different physical conditions. Exoplanets appear in a large range of orbital separations around a variety of stars and therefore are subject to very different stellar irradiations. The properties of the planets depend heavily on their mass, chemical composition, stellar irradiation, and on their interaction with the host stars' gravity, radiation, and magnetic field. Observations have revealed and will continue bringing to light an enormous diversity of planets and planetary systems conforming an exceptional set of laboratories which will challenge our knowledge on physics, chemistry, geology, and biology.

The masses of known exoplanets span the range between the mass of the Earth and several times the mass of Jupiter. While our Solar System provides useful guidance to establish the minimum mass of a planet, observations do not offer a strong indication about the value of a maximum mass. A widely adopted criterion for such value is the deuterium burning limit (13 M_{Jup}). However, objects with masses slightly above, generally designated as brown dwarfs, and below this limit have been found orbiting stars and could in principle form via the same mechanism of gravitational instability in protoplanetary discs, blurring a distinction. Brown dwarfs are defined as self-gravitating objects unable to sustain stable hydrogen burning which according to evolutionary models have masses below 75 M_{Jup} (for solar metallicity). Discovered in 1995, free-floating brown dwarfs are known to populate the galaxy in a comparable number to stars, but are rarely found around stars (with occurrence rate of a few percent). In year 2000, free-floating objects with only a few times the mass of Jupiter were discovered in star clusters via imaging and spectroscopy. Subsequent searches have revealed that free-floating super-Jupiters compare in number to solar-type stars and are far more common as free-floaters than orbiting stars. Establishing an upper limit to the mass of planets will have to await until an adequate understanding of the formation mechanisms of these super-Jupiters is achieved.

Doppler radial velocity measurements provided the first exoplanet discoveries around solar-type stars, the so-called Hot Jupiters, close-in orbit gas giants dominated by a hydrogen-helium envelope with a rocky core. This type of exoplanets was also the first detected to produce eclipses of their stars. While cold Jupiter-like planets of much longer orbital periods appear to orbit around 3% of solar-type stars, their hot counterparts are present only around less than 1%. Hot Jupiters are likely formed via core accretion at much higher separation from their host stars suffering subsequent migration to their observed orbits. Planets with such very close orbits ($P < 7$ days) offer a high probability (10%) of producing eclipses, and many have been the subject of extensive atmospheric characterization via differential photometry and spectroscopy during transits. These observing techniques have provided some initial insight on their atmospheric chemical composition, vertical pressure-temperature profiles, albedos, and circulation patterns.

Among the identified new types of planets, super-Earths, which have several times, the mass of the Earth and sizes up to twice its radius, are remarkably different to the planets in the Solar System. Besides, they are the most abundant planets with orbital periods of less than 100 days and are frequently found in compact multiple-planet systems. More than 50% of the stars seem to host a super-Earth or a smaller planet. The generation of these planets is expected to occur through the formation of a rocky core and subsequent accretion of a gas envelope. The envelopes can be massive enough to notably contribute to the total radius of the planet. However, many processes (photoevaporation, collisions, etc.) contribute to eroding the atmosphere during evolution causing a large diversity of these envelopes, which observations are starting to unveil. Some super-Earths could in principle form a crust and host liquid water, if they are located at suitable orbital separations. Several have been detected in the habitable zone of stars producing eclipses. They are very attractive targets for atmospheric characterization via transit spectroscopy with the new suite of large diameter ground and space telescopes.

Evidence for the existence of terrestrial planets is compelling, and planets with similar mass, size, and physical conditions potentially similar to the Earth have already been discovered. Planet Proxima b in the nearest star to the Sun, detected using Doppler radial velocity measurements, is the closest example of a continuously increasing family. Such rocky planets may host liquid water, and the characterization of their thin atmospheres will be an extraordinary challenge, even for the new generation of extremely large telescopes. Proxima b is not known to transit its parent star, and direct imaging and spectroscopy with coronographs assisted by Adaptive Optics on very large and extremely large telescopes is a promising way to obtain information on its atmospheric properties. Identifying tracers of biological activity will possibly require new technological advances.

The Kepler space observatory and other ground-based observatories have identified a large number of transiting planets, including those of Earth-size. Series of radial velocity measurements of the host stars could in principle achieve a determination of the masses for these small planets, which typically induce radial velocity semi-amplitudes of tens of cm/s in solar type stars. The advent of a new generation of ultra-stable high dispersion spectrographs at very large telescopes (ESPRESSO is the first to achieve 10 cm/s) will make possible such measurements in a fraction of the detected systems, leading to the obtainment of planet densities and further insight on the formation processes of terrestrial planets. In multiple transiting planet systems, transit time variability observations can also provide a determination of masses.

Bright stars with transiting Earth-size planets offer an excellent opportunity to study planet atmospheric properties with JWST and the ELTs. A large effort is currently undertaken to search for transiting planets in the habitable zone of nearby stars using a series of dedicated ground-based telescopes (MEarth, SPECULOOS, etc.) and space observatories (TESS). In the future, other space telescopes like JWST, CHEOPS, and PLATO and the extremely large telescopes (EELT, TMT, GMT) will bring exceptional capacities for the characterization of the atmospheres of a large variety of exoplanets, including the new terrestrials.

This *Handbook of Exoplanets* provides an outstanding vision on the state of the art of exoplanet research, as well as describes the historical evolution of the field from first discoveries to the most recent detections. It includes a revision of the theories of formation and evolution for the various types of planets and the on going effort to characterize both planet interiors and their atmospheric properties. Current knowledge on exoplanet properties is confronted with the detailed information provided by planets in the Solar System and by brown dwarfs. The atmospheres of nearby free-floating brown dwarfs can be studied in great detail and offer important insight and guidance for the exploration of exoplanet atmospheres in a large range of temperatures extending below the temperature of the atmosphere of the Earth.

This book also offers an overview of recent advances in the various techniques employed in the field and shows how progress on direct imaging, radial velocities, transit photometry and spectroscopy, microlensing, astrometry, etc., will enable the path to understanding the origin, evolution, and the physical/chemical properties of the large diversity of planets so far discovered, including those similar to Earth.

Instituto de Astrofísica de Canarias, La Laguna, Spain Rafael Rebolo
February 2018

Preface

About 25 years after the discovery of the first exoplanets by a few scattered pioneers, the field of exoplanetology has developed into a principal branch of astronomy, producing over a thousand scientific articles every year. The underlying central question that motivates most of its activity, "Are we alone in the Universe?" and "What are the origins of our and of other Worlds?" can now be illuminated from several angles, but a conclusive answer remains in the distance. The present work is a first attempt to summarize the current status of the science driven by these questions. The idea for it started almost like a joke during a dinner in a sympathetic Korean Restaurant during the 29th IAU General Assembly in Honolulu. Three years later, that embryo has developed into four heavy volumes, with contributions by over 200 scientists. We, as Editors-in-Chief of this project, are very proud of how our colleagues, partners, friends, and even some scientific rivals have taken a substantial part of their more than busy lives to make this possible. A big "Thank you" to all of them!

The *Handbook of Exoplanets*, like other major reference works by Springer, has been organized into Sections. Each of them was developed under the supervision of one or more dedicated Section Editors. The work of these scholars has been absolutely fundamental for the success of the project. Dear Tsevi, Agustín, María Rosa, Alex, Norio, Malcolm, Roi, Hans, Nuccio, Natalie, Sara, Ralph, Pedro, Vikki, Rory, and Jean, you cannot imagine how thankful we are!

The Handbook is organized along both a chronological and thematic perspective. The first section "Exoplanet Research: A History of Discovery" serves as an introduction for the Handbook. Then, two sections follow that contextualize exoplanets within the wider field of astronomy: "Solar System–Exoplanet Synergies" and "Between Planets and Stars," devoted to the celestial bodies of our vicinity, including the Earth and objects like free-floating planets or brown dwarfs. The major part of the Handbook describes the observational efforts of the last 25 years, namely "Planet Discovery Methods," "Ground-Based Instrumental Projects for Exoplanet Research," "Space Missions for Exoplanet Research," and "Exoplanet Characterization." The central stars are fundamental for our understanding of planet systems, hence the sections devoted to: "Characterizing Planet Host Stars" and "Planets and Their Stars: Interactions." The next section of the Handbook introduces the status of interpretative work in exoplanet science. First, the major global results are given in the section “Catalogues, Planet Abundances and Statistics.” The most detailed knowledge we have about exoplanets is about their atmospheres, hence the section “Exoplanet Atmospheres.” The question about our and other worlds’ origins is directly confronted in “Formation and Evolution of Planets and Planet Systems.” One of the major observational results is our awareness of the variety of other worlds that exist in the Universe, which motivated the section named “The Diversity of Worlds: An Exoplanet Fauna.” The largest section of this book “Where Life May Arise: Habitability” is directly dedicated to the fundamental question “Are we alone?” We do not have a crystal ball suggesting what will be next in our field. However, we felt the necessity to envisage how it may develop; hence, the book concludes with “The Future: What Will Be Next?”

Certainly, there will be colleagues who point out that important topics have been omitted and they will likely be correct. However, this work has been envisaged as a living document in which future developments, as well as updates of current ones, will be addressed in its electronic edition. So, it is open to suggestions and improvements, and we invite readers to provide feedback. Our ultimate hope is that sometimes in the future there will be chapters or whole sections, not devoted to remote observations and exoplanet habitability as of today, but rather to results from in situ missions and to exoplanet habitats. Future provides indeed a wide open window to our understanding of the Universe!

Tenerife, Spain
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Hans J. Deeg
Juan Antonio Belmonte

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About the Editors

Hans J. Deeg is staff astronomer at the Instituto de Astrofísica de Canarias (IAC) in Tenerife, Spain. Born in Würzburg, Germany, he obtained a Master's in Physics from SUNY Buffalo, USA, in 1986 and a Ph.D. from the University of New Mexico, USA, in 1993. Previously, he held posts at the Rochester Institute of Technology; the SETI Institute (both USA); the Centro de Astrobiología, Madrid; and the Instituto de Astrofísica de Andalucía (both Spain). Deeg's principal interests are the detection and characterization of exoplanets, for which he has been working since 1994 on a wide range of ground- and space-based projects. He was the principal Spanish investigator for the exoplanet detection with the CoRoT space mission (2006–2014) and is currently coordinating several tasks for ESA's next-generation PLATO space mission. He is also a habitual user of the large telescopes installed at Roque de los Muchachos Observatory on the island of La Palma. During his career, he has authored over 300 scientific articles mostly related to exoplanets, organized several conferences on this topic, and been member on several review panels for funding agencies or telescope time allocation. Deeg has also supervised several Ph.D. theses and is currently teaching a Master-level course on exoplanets at the University of La Laguna, Tenerife.

Juan Antonio Belmonte is Research Professor at the Instituto de Astrofísica de Canarias (Tenerife, Spain) where he investigates exoplanets, stellar physics, and cultural astronomy. He has published or edited a dozen books and authored more than 200 publications on those subjects. He has been the Director of the Science and Cosmos Museum of Tenerife from 1995 to 2000 and President of the European Society for Astronomy in Culture (SEAC) from 2005 to 2011 and of the Spanish Time Allocation Committee (CAT) of the Canarian observatories from 2003 to 2012. In 2012, he received the “Carlos Jaschek” Award of the European Society for Astronomy in Culture for his contributions to that discipline. He has been editor of two sections and the author of 12 contributions in the previous Springer’s *Handbook of Archaeoastronomy and Ethnoastronomy*. In the early 2000s, he got involved in exoplanet research being one of the founders of the TrES Network and co-Director of one of the first international schools in the field in 2004. He has supervised three Ph.D. students in Exoplanets, including that of Roi Alonso, one of the Section Editors of this *Handbook of Exoplanets*. A member of the Exoplanet Project at the IAC, he is currently teaching a master-level course on extrasolar planets at the University of La Laguna. He is now President of the International Society for Archaeoastronomy and Astronomy in Culture and Advisory Editor of the *Journal for the History of Astronomy*. Born in Murcia (Spain) in 1962, he studied physics and got his master thesis in 1986 at Barcelona University and obtained his Ph.D. in Astrophysics from La Laguna University in 1989.

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