Extrasolar Planets

CANARY ISLANDS WINTER SCHOOL OF ASTROPHYSICS

VOLUME XVI

EDITED BY

Hans J. Deeg, Juan Antonio Belmonte and Antonio Aparicio

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EXTRASOLAR PLANETS

This volume presents the lectures from the sixteenth Canary Islands Winter School, which was dedicated to extrasolar planets. Research into extrasolar planets is one of the most exciting fields of astrophysics, and the past decade has seen research leap from speculations on the existence of planets orbiting other stars to the discovery of over 200 planets to date.

The book covers a wide range of issues involved in extrasolar planet research, from the state-of-the-art observational techniques used to detect extrasolar planets, to the characterizations of these planets, and the techniques used in the remote detection of life. It also presents insights we can gain from our own Solar System, and how we can apply them to the research of planets in other stellar systems.

The contributors, all of high standing in the field, provide a balanced and varied introduction to extrasolar planets for research astronomers and graduate students, with the aim of bridging theoretical developments and observational advances.

Intended for students, researchers, lecturers and scientifically minded amateur astronomers, this book provides a suitable introduction to the field, and can form the basis for a specialist course in extrasolar planets.

Ca a I a d W e Sc A c

Volume XVI

Ed C e
F. Sánchez, *I de A ca de Ca a a*

P e e e e

Participants of the XVI Canary Islands Winter School, in front of the Congress Center in Puerto de la Cruz, Tenerife.

Lecturers and scientific organizers of the Winter School, in front of Mt. Teide. Back row, from left to right: Franck Selsis, Juan Antonio Belmonte, Tim Brown, Stephane Udry, Laurance Doyle and Hans Deeg. In the front: Agustín Sánchez-Lavega and Günther Wuchterl. Not present are James Kasting, Rafael Rebolo and Garik Israelian.

EXTRASOLAR PLANETS

XVI Canary Islands Winter School of Astrophysics

Edited by

HANS DEEG, JUAN ANTONIO BELMONTE,
and ANTONIO APARICIO

Instituto de Astrofísica de Canarias, Tenerife

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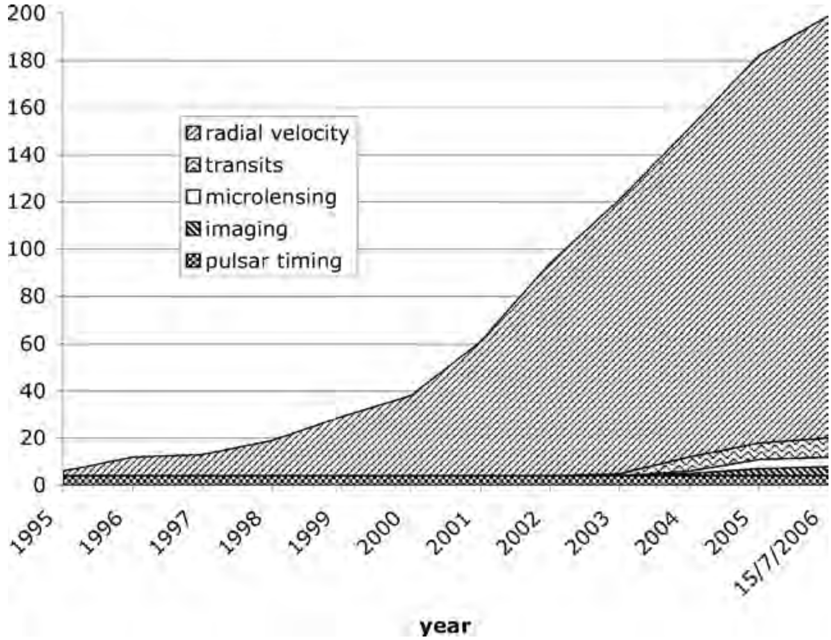
Preface

Contemplating the existence and character of ‘other worlds’ has a long history, giving rise to an ample body of philosophical and artistic works. But only in 1995 could we begin to put these musings on a scientific basis, with the detection of the first extrasolar planet by Michel Mayor and collaborators at Geneva Observatory. Since that time, the field of extrasolar planets (exoplanets for short) has undergone extremely rapid development and has delivered some of the most exciting results in astronomy. Research today on exoplanets has established itself as a major branch of current astronomy. The growing importance of this field can be shown from the rising number of publications in the field. Starting with a few scattered papers over ten years ago, currently about 2% of all of the papers published in astronomy deal with extrasolar planets. Similarly, the number of projects searching for extrasolar planets has risen from five in 1995 to over 70 at present. Training in exoplanets may therefore be considered very valuable for young researchers. Due to the novelty of the subject, new research groups are frequently still being formed, giving excellent opportunities for participation by qualified personnel.

With exoplanetary science essentially starting in 1995 and with its very rapid development in the following years, this topic has hardly found its way into the astronomy/astrophysics curricula taught at universities. There are still relatively few lecturers familiar with the topic. The exceptions are those departments where active exoplanets research is being pursued; in such cases it is typically taught in optional advanced courses. Coinciding with this lack of curricular diffusion is a lack of monographs suitable for university courses. This book is intended to remedy both of these shortcomings; we hope that it may serve as a useful basis for intermediate- to advanced-level university courses.

The milestone of 200 known extrasolar planets has been passed, and over twenty systems of two or more planets orbiting the same star are known. Scientific work on extrasolar planets, however, begins only with their detection. For most planets, their *c a ac e a* is still limited to basic physical parameters such as period and distance to the central star, and to certain further parameters, such as the planet’s mass and estimates of its approximate surface temperature. Only for very few extrasolar planets is significantly more known; the first ingredients of an atmosphere were recently detected for one of them. It will be through these more detailed characterizations that the upcoming observing projects will have the greatest impact. The employment of a wider variety of detection methods (such as transit detection, precision astrometry and interferometry; see the figure on the next page) will give us a wider range of knowledge on these planets in the coming years. Also, the launch of the first space based missions dedicated to exoplanets will lead to a further enlargement in the parameter space of detectable planets, the most desired being the detection of small Earthlike planets. One of the most ambitious goals will be the detection of biological signals on exoplanets. Though very difficult, this goal is already being contemplated in the design of the most advanced space missions that may launch within about 15–20 years.

It is the great interest in communicating exoplanetary research findings to the general public, and the potential for further important discoveries (most notably, potentially inhabitable Earthlike planets) that has convinced all major space agencies to dedicate missions to the detection and characterization of exoplanets. The coming decade will therefore see a series of launches. The first will be the Franco-European *COROT* mission, which will be the first experiment to test for the presence of massive terrestrial planets. This will be followed by NASA’s *Ke e* , which will be the first mission to look for the presence of true Earthlike planets. The most ambitious projects are *Da* (ESA)



Cumulative number of exoplanets, with the method of their detection. Before 1995, only four planets around pulsars, found by timing, were known. Radial velocity detection was the only successful method until 2003, and today maintains a clear dominance on detection rates. Since then, several other methods have had their first successes, allowing a more varied characterization of the detected planets. At the time of writing, there were 179 radial velocity, eight transit, four microlensing and four imaging detections. Together with the pulsar planets, this gives a total of 199 extrasolar planets. (Numbers based on The Extrasolar Planets Encyclopaedia, www.exoplanet.eu.)

and *TPF* (NASA), planned around the year 2020. These missions will attempt the direct detection of Earthlike planets around nearby stars by coronagraphy and interferometry, and perform a fairly detailed analysis of their atmospheres, with the major goal of probing for the presence of biomarkers. Since the first exoplanet was discovered rather recently, a layperson might expect that only very specialized equipment and large telescopes can provide important results in this field. However, small telescopes are also playing an important role, as has been shown by the detection of transiting planets of the stars HD 209458b and TrES-1 with the 10 cm STARE telescope. Currently, an ample variety of small telescopes for similar detections are being constructed or are already operational. These are mainly aimed at the detection of relatively large planets in nearby stellar systems. These planets are still important discoveries, since they allow the most detailed studies with current observing techniques, employing large telescope. Their characterization is also an important driver for the development of future extremely large telescopes, or for the employment of telescopes at very special sites like Antarctica's Dome C.

While current exoplanet science is certainly being driven by observations, a number of theoretical interpretations have undergone a great refinement since the first planet discoveries. These theories are fundamental to our understanding of these objects. They are also needed to formulate the questions that may be resolved by the next generation of observing projects, where they may be drivers for their design. Hence, observers need to have a theoretical understanding in order to be able to define observing projects that are able to advance theory. This book addresses this duality between observation and theory. Its principal contents are an observational part dealing with planet detection methods and giving a description of the current state of knowledge from observations. This is followed by a theoretical part on the formation and evolution of planets, with a section devoted to habitability and biomarkers.

Once the first Earthlike planets have been discovered, we expect that this field will become a melting pot for activities of astronomers, paleontologists, geologists and biologists alike. Surely, the subject of extrasolar planets will undergo an exciting development, of which we are currently witnessing only the beginnings.

The Editors
La Laguna, Tenerife

Acknowledgements

The organizers of the XVI Canary Islands Winter School would like to express their sincere gratitude first and foremost to the lecturers, for making it a great scientific and scholarly event. Preparing the lectures, attending the school and writing the chapters for this book has been a major, but we hope rewarding, commitment in their very busy agendas. We specially acknowledge Tim Brown who, despite a strong familiar concern, was able to make his way to Tenerife, and to Agustín Sánchez-Lavega who, despite a major personal event, had the time to offer us a fascinating perspective of our Solar System, including Pluto's very recent loss of planetary status. Terry Mahoney, of the IAC's Language Correction Service, had a major part in the creation of this book, revising minutely and with enormous patience all submitted manuscripts, from native and non-native English speakers equally, and this book would not have been possible without him.

The soul of the school has been without any doubt our secretary Nieves Villoslada. Without her help, diligence and permanent availability the school would have not worked as perfectly as it did. Her colleague Lourdes González was also very helpful on many relevant occasions. Jesús Burgos of the OTRI at IAC, one of the most efficient persons we know of, provided invaluable help with all the issues concerning the preparation of applications needed to receive sufficient funding. The school's poster was prepared by Ramón Castro and offers a vision of extrasolar planet research that may entice young scholars to enter this field. For Carmen del Puerto and her team at the Gabinete de Dirección of the IAC the Winter Schools are a time of great pressure, since they have to prepare a special issue of the IAC *N c a* Newsletter for the end of the school, a task they accomplished excellently. The dedication and enthusiasm of all these people is an essential ingredient to the Canary Islands Winter School Programme, and is warm-heartedly acknowledged.

We greatly acknowledge the financial assistance from the Spanish Ministerio de Educación y Ciencia and from the Cabildo de Tenerife who kindly provided the excellent facilities of the Congress Palace of Puerto de la Cruz where the event took place. The Ayuntamiento of Puerto de la Cruz generously offered all participants a very nice banquet at the restaurant Casa Régulo. This was one of the most intimate moments of the school when, after two weeks of apparent seriousness, a group of the students started performing short sketches, pulling the legs of both organizers and lecturers. Many thanks for such a delightful and unforgettable moment! Last but not least, we would like to acknowledge all the participants of the school, both lecturers, students and supporting personnel when they, even under exceptional circumstances like the visit at IAC of the Spanish Crown Prince Don Felipe and his wife, provided the finest ambience one could imagine for such an event.

1. Overview of extrasolar planet detection methods

LAURANCE R. DOYLE

In this chapter we will describe in a general manner each planet detection method and examine the fundamental astrophysical parameters each technique measures as well as its present measurement limitations for the detection of inner giant planets, jovian outer planets, and Earthlike planets. We then outline several secondary detection methods that may be instituted in the near future with increased detection sensitivity. We then discuss the ranges of each detection method and sketch several cases in which additional parameters may be derived through the acquisition of data from several methods combined. In the final section we discuss habitable zones around M-dwarf systems as potential near-term targets for the detection of life-supporting planets.

1.1. Introduction

In the following sections an overview of the main methods of extrasolar planet detection is presented. This is not a historical review – an excellent review, for example, can be found in Perryman (2000) and the 469 references therein. It is also not an up-to-date listing of extrasolar planet detections or candidates; these can be found at the comprehensive site of the *E a a P a e E c c ed a* by J. Schneider (www.obspm.fr/encycl/encycl.html). In this chapter we do, however, describe in a general manner each detection method and examine the general astrophysical parameters each technique measures as well as its present measurement limitations. We mention some secondary detection methods that may find application in the near future and what additional parameters may be derived through the acquisition of data from several methods combined. We finally discuss M-dwarf star habitable zones, as these are likely to be the near-term targets for the detection of exobiology on extrasolar planets. This chapter is aimed, in explanatory detail, at the interested college student level.

We note that the detection parameters for the pulsar timing, radial velocity, astrometric imaging, reflected light and eclipsing binary timing methods depend, at any given time, on the orbital phase, $\varphi(t)$, of the extrasolar planet, which is a function of the geometry involved in that detection method. However, detectability depends on the maximum signal produced for a given method, and it is this that we formulate in the equations below. However, we shall point out at which phases this maximum occurs. In keeping with eclipsing binary protocol, the planetary orbital phase $\varphi(t) = 0$ degrees will be when the (darker) planet is in inferior conjunction, that is when it is closest to the observer.

1.2. Pulsar timing

Unexpectedly, the first planetary-mass objects detected around another star were closer to terrestrial-mass than to jovian-mass. The parent star was the pulsar PSR B1257+12, 500 parsecs distant, and the two planetary objects detected around it are a 2.8 Earth (projected) mass ($M_\oplus$) body with a period of 98.22 days and a 3.4 $M_\oplus$ body with a period

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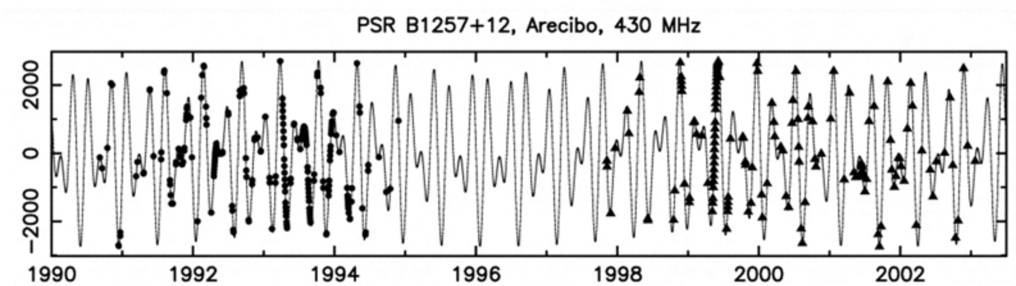

FIGURE 1.1. Time of arrival residuals (in microseconds) of 430 MHz signals from the 6.2-millisecond pulsar PSR B1257 + 12 (from Konacki and Wolszczan 2003) showing that the residuals are dominated by the Keplerian orbits of two planets of actual mass 4.3 (B) and 3.9 (C) Earth-masses (of three in the system, the third being very close to the pulsar). These planets are nearly coplanar (around 50 degrees orbital inclination) and are in actual 3:2 orbital resonance with each other (66.5 and 98.2-day periods; planet A having a period of 25.3 days).

of 66.54 days (Wolszczan 1994; Wolszczan and Frail 1992). The precise radio pulse rates of pulsars (seconds to milliseconds) and their stability as timing ‘clocks’ (variations in pulse timing on the order of only about a trillionth of a second per year) allow variations in the position of the pulsar to be measured precisely. The variation in timing can occur due to a positional shift in the pulsar around the pulsar–planet barycentre. If such a second mass (planet) is in orbit around the pulsar, the two bodies will orbit around a mutual barycentre, each distance from the barycentre being determined directly by their mass-ratios, where M_* and a_* are the mass and distance (semi-major axis) from the barycentre to the centre of the pulsar and M_p and a_p are the mass and distance from the barycentre to the planet. The motion of the pulsar around the barycentre causes the addition of (or subtraction of) the light travel time across this distance, which will result in a delay (or early arrival) of the periodic variations in the timing of the pulsar pulses. For a planet in a circular orbit, the maximum amplitude of the delay time will be:

$$\tau = \sin i \left(\frac{a_\mathrm{p}}{c}\right)\left(\frac{M_\mathrm{p}}{M_*}\right), \tag{1.1}$$

where i is the inclination of the planet’s orbit ($i = 90°$ being edge-on), and c is the speed of light. The pulses will be ‘on time’ at phases $\varphi(t) = 90$ and 270 degrees, late by an amount τ at $\varphi(t) = 0$ degrees, and early by an amount τ at $\varphi(t) = 180$ degrees orbital phase angle, where zero degrees phase is when the planet is closest to the observer (i.e. inferior conjunction). Note that the sine function in Eq. (1.1) is not negative because it is the pulsar signals that are being measured directly, and the pulsar is at the opposite orbital phase from the planet. Thus, via the foreshortened light travel time across the stellar-barycentre distance, the pulsar timing method can measure the projected planet-to-star mass ratio, the true orbital period of the planet (or planets), and its orbital eccentricity (if the orbit is not circular). General relativistic precessional phase drifts may allow further constraints on the pulsar mass, but only for closer-in planets over longer observing times (see Figure 1.1).

If we define a typical close-in extrasolar giant planet (CEGP) as a 3 jovian-mass planet with a circular orbital semi-major axis (i.e. orbital radius) of 0.05 AU (astronomical unit), and a ‘Jupiter’ and an ‘Earth’ as planets with the mass and orbital location (distance from their star) of Jupiter and Earth in the Solar System, respectively, then the half-amplitude timing offsets for such planets around a typical pulsar (assuming the pulsar to be 1.35 solar masses) would be $\tau = 140$ milliseconds (ms) for a CEGP, 1.65 seconds for a 'Jupiter', and 3 ms for an 'Earth'. That is, these will be the expected maximum delays in the pulse arrival times at a planetary orbital phase $\varphi(t) = 0$ degrees.

1.3. Periodic radial velocity variations

The radial velocity or 'Doppler shift' method has been the most successful extrasolar planet detection method to date, detecting the vast majority of planets as of this writing. The first extrasolar planets around solar-type stars were discovered in this way (Mayor and Queloz 1995; see also Marcy and Butler 1998 and reference therein). Radial velocity variations again cause a wobble in the parent star, but the stellar light flux is generally very constant, so that timing of variations cannot be used to detect this stellar offset around the star–planet barycentre. However, very high precision spectral line measurements (one part in a hundred millionth of a spectral line width) can be performed by superimposing a comparison spectrum with many lines (like an iodine cell in the light path at the observatory) on to the stellar spectrum for a precise measurement of periodic movement in the star's spectral lines.

The stellar spectral lines will move periodically redward or blueward due to the Doppler shift by $\Delta\lambda/\lambda = v/c$, caused by the periodic motion, with a maximum velocity v of the star about the star–planet barycentre. Again, the spectral line variations only measure the component of the motion directly towards or away from the observer, and hence the mass of the body (planet) causing the reflex motion of the star is a minimum mass measurement for the planet, $M_\mathrm{p} \sin i$. The maximum amplitude of this periodic radial velocity variation is given by:

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_\mathrm{p} \sin i}{(M_\mathrm{p} + M_*)^{2/3}} \frac{1}{(1 - e^2)^{1/2}}, \tag{1.2}$$

where P is the planetary orbital period, e is the planetary orbital eccentricity, and G is the gravitational constant. K, P and e can be derived from several measurements of the Doppler shift during a planet's orbit. The maxima in K will occur at planetary orbital phases of $\varphi(t) = 90$ degrees (blueshift of stellar spectra lines) and $\varphi(t) = 270$ degrees (redshift of stellar spectral lines). With knowledge of M_* from stellar classification (typically based on low-resolution spectra), the term $M_\mathrm{p} \sin i$ can then be derived. Kepler's third law, $(P/\mathrm{yr}) = (a_\mathrm{p}/1\mathrm{AU})^{3/2}(M_*/M_\odot)^{-1/2}$, where $M_\odot$ is one solar mass, allows then also a derivation of the semi-major axis of the planet.

The precision possible for this detection method is about 1 m/s, this limit imposed by intrinsic stellar surface fluctuations – i.e., variations present in even the most stable solar-type stars (see Figure 1.2). For a CEGP the radial velocity amplitude will be about 56 m/s, for a 'Jupiter' about 13 m/s, and for an 'Earth' about 0.1 m/s. Thus this method may not be expected to detect Earthlike planets around solar-like stars but can, however, detect any jovian-mass bodies within a star's circumstellar habitable zone (CHZ).[1] Hypothetical Earth-sized moons around such bodies have been suggested as being of interest to exobiologists. The detection of Jupiterlike planets are of interest both because of their comparability with our own Solar System as well as the ability of jovian-type planets to remove cometary debris, serving as a possibly necessary 'shield' for any biosystems developing on the inner terrestrial planets of the star system. This method is also, at

[1] The circumstellar habitable zone (CHZ) is defined here as the distance regime around a star where liquid water can persist on the surface of a sufficiently large planet. For a discussion of the CHZ see Chapter 8.

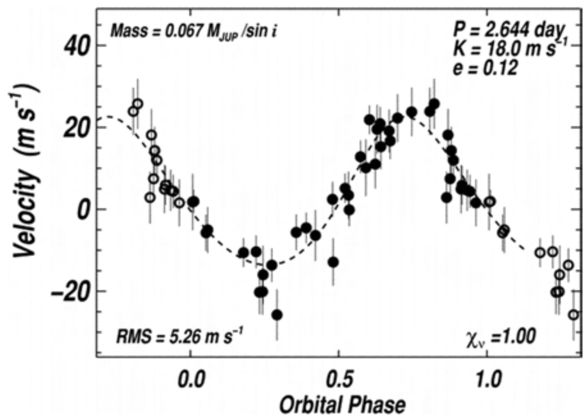

FIGURE 1.2. A Neptune-mass planet orbiting the nearby 0.41 solar-mass M-dwarf GJ 436 (from Butler *et al.* 2004). The 18.1 metre/second variation in the spectral lines of the star with a period of 2.644 days is caused by a planet with a projected mass of about 1.2 Neptune-masses.

present, limited to detection of planets around fairly stable, single star systems as the measurement of these radial velocity variations demands such high spectral line precision measurements.

1.4. Gravitational microlensing

Due to general relativistic effects of bending spacetime, a star moving very close to alignment with a background star will bend – that is, focus – the light of the background star, causing a temporary increase in the combined brightness of the stars by amplifying the light from the background star. The phenomenon, first observed with galaxies, is known as gravitational lensing, A perfect stellar alignment will cause symmetric images around the lensing star; this is known as the ‘Einstein ring’ (or sometimes an ‘Einstein cross’). The Einstein ring radius is given by:

$$R_{\mathrm{E}} = \left[\frac{4GM_{*\mathrm{L}}}{c^2}\frac{(D_{\mathrm{S}}-D_{\mathrm{L}})\,D_{\mathrm{L}}}{D_{\mathrm{S}}}\right]^{1/2}, \tag{1.3}$$

where $M_{*\mathrm{L}}$ is the mass of the lensing star, D_{L} is the distance to the lensing star and D_{S} is the distance to the source star. The angle on the sky of the Einstein radius (the Einstein angle) is then given as: $\theta_{\mathrm{E}} = R_{\mathrm{E}}/D_{\mathrm{L}}$. The microlensing magnification, which varies with time, is given by:

$$Q(t) = \frac{u^2(t)+2}{u(t)[u^2(t)+4]^{1/2}}, \tag{1.4}$$

where $u(t)$ is the projected distance between the image of the lensing star and the source star in units of the Einstein radius (Perryman 2000). We can see that for an exact alignment the magnification would become infinite, theoretically. If a planet is in orbit around the lensing star, then observable deviations from the amplification pattern given by Eq. (1.4) may occur, which are caused by a planet-mass distorting the stellar gravitational field.

The probability of alignment among two stars is, even in the Galactic Centre, only about one in 10^6, but once a star is aligned with another star the probability that a planet may also cause an amplification that exceeds 5% of the brightness of the star’s amplification itself becomes about one in five (Schneider *e a* . 1999). For this superposition