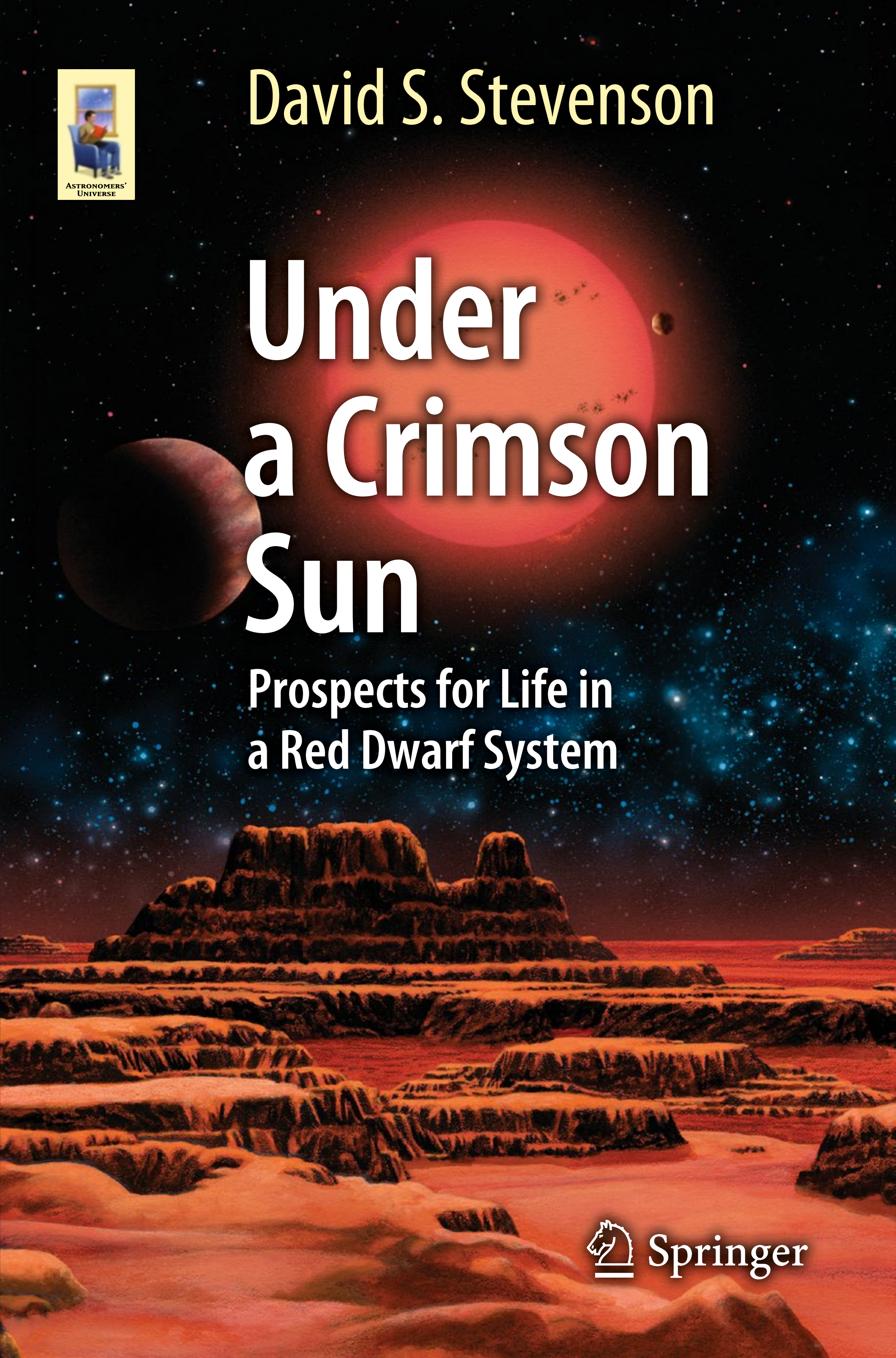

ASTRONOMERS' UNIVERSE

David S. Stevenson

Under a Crimson Sun

Prospects for Life in a Red Dwarf System

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Sherwood, UK

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For my wonderful and long-suffering wife Nikki, and for my children Aleister, Oran, Arabella, Genevieve, and Vincent

Preface

Initial ideas regarding the habitability of extrasolar planets have focused on the overall size of the planet and its location within the stellar habitable zone. However, many additional factors exist that affect their potential ability to harbor life. This is particularly true of planets orbiting red dwarf stars, for it is these worlds that will have the most time to evolve within a star's Goldilocks zone.

Red dwarf stars live for hundreds of billions or trillions of years, providing a very steady candle with which to light their retinue of worlds. However, red dwarfs throw up a wealth of seemingly contradictory conditions that grossly affect whether a planet will be habitable. Planets orbiting these little crimson suns have a unique set of problems that could, in principle, prevent or reduce their potential to host life. Are the most habitable worlds discovered to date really as they appear?

This book follows the ongoing work of researchers studying the many disparate branches of science, including astrophysics, chemistry, geology, and biology. Their aim is to create a more holistic view of habitability, based around a large number of interlinked factors. In essence, the question of habitability cannot be reduced to an answer based solely on the location of a planet within or outside of its star's Goldilocks zone. This book first explores the nature of the stars and then the planets that orbit them. By considering all aspects of planetary existence, a picture then emerges as to how habitable any planet orbiting a red dwarf can be.

In the making of this book, there were a number of different areas of science that needed investigation. As such, I would like to offer particular thanks to Greg Laughlin (University of California, Santa Cruz), with whom I had many productive discussions regarding the evolution of the lowest-mass stars. Notably it was clear that inexplicably little if any work had been published on

the evolution of the orange (K) dwarfs. Aside from one publication in 1993, this area of astrophysics hasn't been visited since. The evolution of these stars was then inferred from work carried out by Greg on red dwarfs, as well as a diverse set of publications on a set of stars called extreme horizontal branch stars. Greg provided some useful clues that validated my assumptions. This is an area of research to which astrophysicists must return. This is all the more true as K-class, orange dwarfs have become targets for searches of habitable worlds.

I would also like to offer thanks to the team at www.universe-today.com for their prescient (verging on spooky) ability to publish articles on topics I was writing about at the time. The work of this website's authors often alerted me to very recent research that was either unpublished or had just been so.

Finally, the book has many areas that are as yet untested hypotheses. In the coming years, Kepler and other telescopic probes will begin to test these ideas, adding meat to the bones of contention and theory. These are exciting times.

Sherwood, UK David S. Stevenson

About the Author

David Stevenson studied molecular biology at Glasgow University where he attained a First Class BSc. Honors. He then continues is studies towards a PhD in molecular genetics at Cambridge. Further qualifications in with the Open University include a Distinction in Astronomy and Planetary Science, and separately Geophysics and Geochemistry. His peer-reviewed biological research articles from 1999 to 2003 include a paper on the early development of life, "The Origin of Translation," published in the *Journal of Theoretical Biology*.

David's interest in astronomy was encouraged from an early age by his father. This (combined with an interest in explosions!) has led David to research and write about the life and death of stars.

After a stint in academia, David became a teacher but continued to write scientific articles for various publications. He has published numerous articles on the Blackwell Plant Sciences website (2002–2007). "Turning Out the Lights" (an article about red dwarfs) was published in *Popular Astronomy* in 2003, "A Bigger Bang" (about Type Ia supernovae) in *Sky & Telescope* in July 2007 and "Supercharged Supernovae" (cover article in Sky & Telescope, October 2011). "He is currently completing a second book for Springer (Extreme Explosions" which is due for publication in September 2013.

David lives in Nottingham in the UK with his wife and family.

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1. The Discovery of Extraterrestrial Worlds

Introduction

Spinning wildly, with hundreds of revolutions per second, is the millisecond pulsar PSR B1257+12. Not the most glamorous-sounding object in the known universe. Yet any millisecond pulsar has led an extraordinary life. Its first breath is taken in the multi-billion-degree plasma generated in the heart of a collapsing star. As the star falls apart, the core is crushed into a fast-spinning ball of neutrons, iron and elementary particles. This is a pulsar, a spinning neutron star. The pulsar generates beams of electromagnetic radiation that sweep outwards from its magnetic poles, scanning surrounding space like the silent beams of a distant lighthouse.

However, at the point of stellar detonation this freshly minted neutron star doesn't cavort with a millisecond pulsar's wild abandon. At this stage, as the debris of the shattered star clears, the pulsar spins slower than a conventional washing machine, perhaps at a few dozen times per second. Over time, normally these pulsars slow and fade from view.

The forerunner of a millisecond pulsar has a different life ahead. Sharing space with a companion star, the intense gravitational field of the neutron star whisks material away from the companion, forming a disc of material around its waist. This accretion disc steadily adds mass to the neutron star. As the pulsar gains mass and momentum, the incoming material spins up the neutron star until it rotates at hundreds of times per second. With increased vigor, the neutron star is reborn as a millisecond pulsar. Its gyrating beams of radiation now rapidly erode what remains of its once vibrant companion.

Pulsar PSR B1257+12 wasn't done yet. Rather than sweep the withered remains of its companion under the cosmic carpet,

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the considerable gravity of PSR B1257 + 12 gently nudged what remained into stable orbits. Over the course of the next few million years, the gas-depleted wreckage of the former companion star were molded into a handful of planets. Liberating no detectable radiation of their own, these ghosts of the former Sun betrayed their presence through their subtle gravitational interplay with the pulsar host.

Many millennia later, Aleksander Wolszczan and Dale Frail noticed that the flashes of radiation from this millisecond pulsar varied slightly, as if it was gently but repeatedly being pulled in different directions. Rather than a steady stream of blips, slight variations in arrival time meant that something, or rather some small things, were orbiting it. Judging by the mass these were planets. Not surprisingly, given the nature of the star around which these planets were orbiting, many in the astronomy community were more than a tad skeptical. In part this was down to history. A year earlier Andrew G. Lyne had announced the presence of a planet orbiting PSR 1829–10. However, this paper was later retracted, leaving an atmosphere that was perhaps not surprisingly suspicious. Yet in the case of Wolszczan's and Frail's discovery, the data was sound: planets did orbit this defunct star. Wolszczan and Frail had bagged three firsts: the first confirmed extrasolar planets, the first multi-planet system, and finally the first super-terrans – planets with only marginally more mass than Earth.

Pulsars, odd planetary hosts aside, hold one further record: the oldest planetary system known. Orbiting within the dense stellar core of the globular cluster M4 is a pair of dead stars, PSR B1620-26 and its companion white dwarf. Announced in 2003, this 12.7 billion-year-old system holds a planet with twice the mass of Jupiter in a distant orbit around both corpses. Although this ancient world was probably born in an orbit around the progenitor of the white dwarf, PSR B1260-26b is now locked in orbit around both stars. A distant, peculiar world.

In 1989, a few years before a skeptical audience accepted the presence of Wolszczan's and Frail's pulsar planets, three Canadian astronomers had delivered what would become proof of principle – a successful method used subsequently to detect hundreds of other worlds. Bruce Campbell, G. A. H. Walker and Stephenson Yang used a technique known as radial velocity (described below) to look for the gravitational effect of a planet as it orbited its star. The technique involves looking for the subtle to-ing and fro-ing of the spectrum of a star as a planet moves it gently towards then away from an observer with each orbit.

The presence of an orbiting Jupiter-sized world was implied by what was then cutting-edge spectroscopy. However, the signal was just on the edge of what could reasonably be detected above instrumental noise, and to add to their woes the astronomers had thought that the star was a giant, giving them a misleading impression of its mass and hence companion's planet mass. Gamma Cephei Ab was one half of a binary system. Most skeptics assumed the team had measured not the effect of an orbiting planet but rather the orbital period of both stars in the relatively poorly classified binary. Therefore, for over a decade, the presence of this world lay in limbo. It wasn't until 2003 that improvements in the radial velocity technique finally confirmed that a Jupiter-mass planet orbited Gamma Cephei Ab with a period of 2½ years.

Throughout the early 1990s refinements in spectroscopy and computer technology led to the discovery of the first planets around more conventional stellar partners. Much like water escaping through the crack in a dike, the first discoveries were faltering, hesitant affairs with a relatively long hiatus between each announcement. But by 2000, discoveries were monthly, then weekly, until a total of over 400 worlds were banked. Initially, the majority of these came through the radial velocity technique used by Campbell and described below. However, as technology has swept forward with increasing pace, more difficult techniques have come to the fore. In this first chapter, we examine the techniques and many of the milestones of exoplanet discovery over the last 20 years.

Radial Velocity: The Pull of Extrasolar Planets

In most stellar spectra, chemical elements betray their presence with fine absorption features. As a star and any planets orbit their center of gravity, the pull of any orbiting planet causes the star to wobble in space. This is associated with minute accelerations

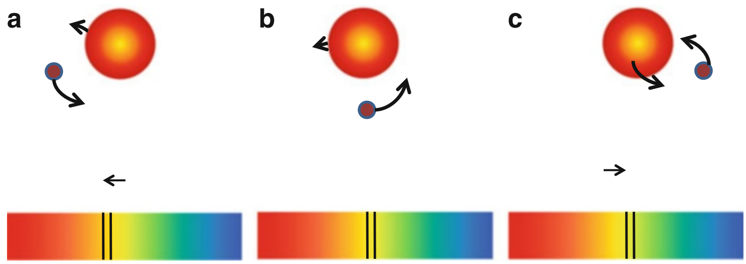

Fig. 1.1 The radial velocity (or RV) method of planet detection. Utterly simple in its science yet fiendishly difficult to use, the technique relies on the precise and accurate interpretation of stellar spectra. Both the planet and star swirl around their common center of gravity. The hidden planet reveals itself by the subtle motion of spectral absorption features to the *red* or *blue* end of the spectrum. Movement to the *blue* end occurs as the star moves towards the observer, and to the *red* end as it moves away

towards and away from the observer as the star orbits its center of gravity. In turn, this effect is manifested as backwards and forwards migrations of stellar absorption lines relative to their resting spectral location (Fig. 1.1).

The amount of wobble varies with two parameters: the relative masses of the star and the planet and the distance between each. The underlying physics is simple. This changes the radial velocity of the star and gives its name to the technique. Although the technique is simple in principle, it does require prolonged and precise observation of the absorption features in the stellar spectra. Where a planet is massive and orbits its star tightly, the wobble stands out from the background noise (Fig. 1.2).

The problem with the technique is that the stellar wobble is minute, perhaps 12 m per orbit of a Jupiter mass world in a tight orbit around a Sun-like star. If you want to find a smaller world in a more distant orbit then your resolution – the ability to discern variability above background noise – must be correspondingly greater. An Earth-mass world pulls with less force than is required to shift its star by a meter. If the orbit of this planet lies within the habitable zone of its star, this weak wobble is extended over 12 months. As radial velocity measurements depend on the precise determination of the location of stellar absorption lines, any interference from atmospheric turbulence or instrument error

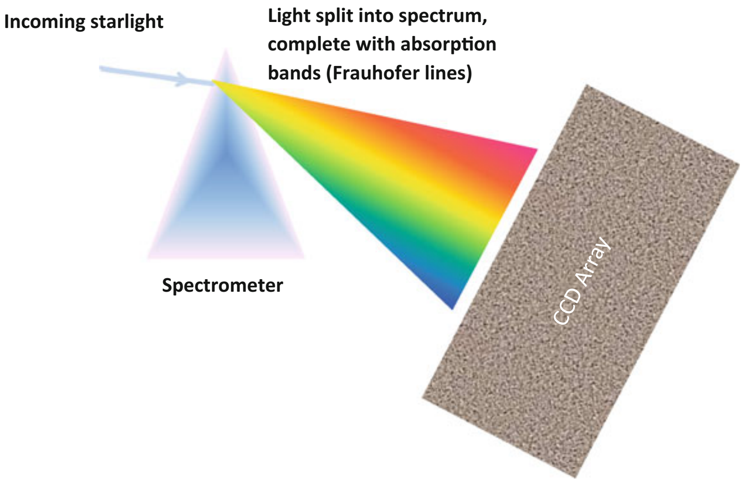

Fig. 1.2 A graphic representation of how the radial velocity system operates. Incoming starlight is split into a fine spectrum. This is compared to a reference spectrum on a separate CCD array. As the star swings around the system's center of gravity the shifts in the position of absorption (Fraunhofer) lines are detected on the array. This subtle shift (less than one pixel in width) is sensed, and the mass of the planet then determined through the amount of shift. These measurements are repeated for several planetary orbits around the star. In order to operate with high precision the system must be extremely stable and free from any random motion that generates noise

can result in spurious identification of planetary signals. As all of the current instruments deployed to use this technique are Earth-bound our atmosphere presents the biggest problem in the successful isolation of planetary signals.

Furthermore, although a single world orbiting a star produces a nice, clear wobble, additional worlds lying further out produce more subtle resonances that become harder to detect as the number of worlds increases. The number of measurements is of necessity increased, and the sensitivity of these measurements must be greater. Unfortunately, this can lead to noise swamping the signal – or spurious signals emerging from the noise. A common method of avoiding this problem is the use of a reference spectrum. Oxygen was proposed some years ago, but it is the use of an iodine reference that was most widely employed until the rise of HARPS (discussed below).

In the iodine reference model, astronomers pass light through a vessel containing iodine, and the resulting spectrum is compared to the stellar spectrum. The absorption features of iodine are well characterized and can be compared with absorption spectra from the star to root out instrumental noise. Much of the detected variability is caused by atmospheric interference or by thermal motion within the instrument itself. The use of the reference source allows some of the instrumental noise to be tracked and its influence reduced.

In the mid-1990s the radial velocity technique was sufficiently well tested, and its sensitivity improved so that it could be deployed effectively in the field. In 1995 Michel Mayor and Didier Queloz published the first confirmed extrasolar planet orbiting a conventional Sun-like star, 51 Peg b. The word conventional was somewhat loosely applied and only to the star. This was a planet approximating Jupiter in mass, but orbiting its star so tightly that it broiled at over 700 °C. 51 Peg b was the first "hot Jupiter."

Over the ensuing years, subsequent discoveries revealed that these hot Jupiters were really rather common. Perhaps it was our *cold* Jupiter that was the exception. The radial velocity technique is by definition very selective. Given often limited observation times, and the (initially) restricted resolution, the radial velocity technique was always bound to identify the freakish, tightly orbiting worlds. After all it is these worlds that have the most immediate impact on stellar motion and hence spectra. The (initially) low resolution of this technique just couldn't identify smaller worlds as readily as it could the larger, hot-Jupiter mass planets.

Over time the precision of the instruments used to detect planets has improved. In the late 1980s a planet had to swing by its star by more than 10 m/s to stand a chance of discovery. In 1993 Keck's HIRES echelle spectrometer began operation. Conceived by Steven Vogt, this instrument was to capture half the subsequent planet finds, using the RV method. To give an idea of the sensitivity of HIRES and competing instruments, the captured spectra will show variation in the location of spectral bands less than 1/1,000th of a pixel in its CCD array. This sensitivity was improved further with an upgrade in 2003 that allowed HIRES to detect the stellar wobbles caused by Neptune-mass worlds orbiting within the radius of Earth around the Sun. HIRES would later go on to capture evidence for three of the four confirmed super-terran planets orbiting Gliese 581. HARPS would complete the job.

The European Space Observatory's 3.6-m telescope at La Silla in Chile is home to HARPS (*H*igh *A*ccuracy *R*adial Velocity *P*lanet *S*earcher) and takes the idea of using a reference spectrum to constrain resolution to another level altogether. Starting in 2003, HARPS employed thorium rather than iodine to produce its reference spectrum. However, to reduce noise, the whole system is chilled to 0.01 K with liquid helium – a fraction of a degree above absolute zero. This super-chilled spectroscope then sits snugly within a vacuum chamber. The combination of minimal atmospheric disturbance and limited particle motion at these low temperatures ensures that HARPS can resolve stellar wobbles down to 30 cm/s – enough to resolve Earth-like worlds in sufficiently tight stellar orbits, or super-terrans in more distant ones. Whereas most RV systems are limited by instrument noise, the extreme localization of the HARPS spectrograph means that it is the idiosyncrasies of the stars themselves that restrict HARPS's unique precision, not the instrument.

Directed by Peg 51b's discoverer, Michael Mayor, and accompanied by Didier Queloz and Stéphane Udry, HARPS holds a number of notable finds, including the first potentially habitable planet GLIESE 581d, added to the three siblings found using HIRES at Keck. Currently, it is HARPS data that forms the basis for argument and counter-argument regarding the existence of another habitable world – Gliese 581d's sibling, planet "g." More on this later in the book.

Through the late 1990s the first planets were found around red dwarfs. Gliese 876b was the first of these, a rare Jupiter-mass planet in a tight orbit around its red dwarf host. In 1996 the first multi-planet system orbiting a main sequence star was confirmed using the radial velocity method, Upsilon Andromedae. It contains three planets, all of which are Jupiter-like. Planets b, c and d were announced in 1996, 1999 and 1999 respectively. With the exception of planet d, all orbit within 1 A.U. of their host star. Planet d, with an orbit of 2.54 A.U., would place it in our Asteroid Belt, making it at best lukewarm and therefore one of the first worlds to be found that wasn't roasting in the light of its host.

Another first for the radial velocity method came in 2001 with the discovery of Iota Draconis b – the first exoplanet found orbiting a red giant. Technically an orange (K-class) giant, the survival of Iota Draconis b confirmed that the rise of the red giant phase didn't mean the annihilation of the entire star system. Not surprisingly, planets far enough removed from the expanding giant can hang on. Iota Draconis b is a particularly massive planet in an eccentric orbit that carries it on average 1.3 A.U. from the center of its star. The orbital eccentricity, coupled to its high mass, meant that its orbital signature was easy to separate from the effects of stellar pulsations, something giant stars are prone to.

In the early 2000s the radial velocity technique had been refined to allow it to detect first Neptune-mass worlds, then super-terrans. The first of these was the second of a pair of planets found orbiting the star Mu Arae c. In August 2004, the HARPS team discovered a planet orbiting Mu Arae with a mass of approximately 14 times that of Earth. Assuming a composition similar to the giants in our Solar System it was most likely a hot twin of Neptune. However, a rocky composition would make it a particularly massive super-terran – a rocky planet resembling a scaled up version of Earth.

Two important scientific advances allowed astronomers to detect planets with masses marginally greater than Earth's. Not only had technology improved sufficiently to detect them, but there was also a reappraisal of the habitability of red dwarfs. This meant that planetary hunts refocused on these small stars rather than the heliocentric pursuit of Earth-like planets orbiting Sun-like stars. With Gliese 876b already in the bag and a hint that other, smaller worlds were also present in the same system, the hunt was on.

Red dwarfs have one big advantage over more massive stars. The center of gravity between the star and its orbiting world is located further from the center of the star than it is with a more massive, Sun-like star. Thus a smaller planet has correspondingly bigger pulling-power around a red dwarf than it would have if it orbited the Sun, and the radial velocity method is more able to detect such a planet in orbit around even a low-mass red dwarf.

Although astronomers waited for technology to improve further, potentially habitable worlds could be found around red dwarfs. Most significantly the orbital period of a habitable planet – the time a planet takes to orbit its star – is small if the star has a low mass and low luminosity. Red dwarfs, therefore, make ideal candidates to search using the radial velocity technique. With the increasingly positive appraisal of red dwarfs as candidate-hosts for life-bearing planets, the radial velocity method took on a renewed vigor as it was used to search for terrans and super-terrans – planets with masses approximating Earth, in the stellar habitable zone.

Transit: The Shadow of a Planet Cast by Its Star

The transit method is a search for the shadow of a moth in a car headlight – when the car is a few hundred meters away. Ground-based observations are effectively worthless. Variations in stellar brightness caused by the transit of a planet across the face of its star are readily swamped by the effects of clouds, atmospheric turbulence – or perhaps the occasional moth looking for food in the night.

Yet, take a probe high above the atmosphere of Earth, lock it securely so that it faces steadfastly in one direction, and you've got the perfect instrument to look for transiting worlds. Although the Hubble Space Telescope had successfully identified the planet HD 209458b using the transit method in 2004, this was a piggy-back discovery. The planet had already been found using the radial velocity technique. That said, Hubble not only confirmed a proof-of-principle, but it also showed that sufficient resolution might be obtained from transit data to determine part of the composition of a planet's atmosphere. Some of the light passing through the planet's gases was absorbed, yielding precious additional spectral clues that could be subtracted from the stellar glare.

Lurking within the data was the spectral signature of sodium vapor. HD 209458b orbits its host Sun so tightly that its broiling atmosphere is boiling off into space, leaving a comet-like tail of hydrogen-rich debris enveloping the planet. Later analysis confirmed that the sodium vapor was found within the extended hydrogen-rich atmosphere at a level corresponding to the planet's stratosphere.

A year later, the Spitzer infrared telescope captured the infrared radiation emitted by two planets: the first of these was HD 209458b, and the second, another hot Jupiter, TrES-1. HD 209458b was observed by Jeremy Richardon (Goddard Space Flight Center) over a range of 7.5–13.2 μm (millionths of a meter). In both cases the emission spectrum provides far more detailed information than the limited absorption spectrum captured by Hubble. Detailed spectral emission lines indicated hydrogen and carbon monoxide, but oddly not water vapor, which had been expected. There was an additional strong peak at 7.78 μm, which was unexplained, and a further peak near 10 μm, attributed to silicate dust – vaporized rock. Later in the same year a separate group identified water using a slightly different technique. These studies opened the gateway on the study of exoplanetary atmospheres and prepared a pathway to the investigation of habitable exoplanets.

In 2007 the transit method was used to identify further molecules within the atmosphere of a distant world. NASA's Carl Grillmair used Spitzer to observe HD 189733b. Analysis of the atmosphere of this hot Jupiter revealed the presence of water and methane. Although it was clearly not a planetary abode for life of any sort, the presence of both methane and water meant the basics of the chemistry of life were present. Indeed, this was the first detection of methane in the atmosphere of any planet outside our Solar System and laid down an important foundation for the future detection of hospitable worlds through their atmospheric chemistry.

Important though Hubble and Spitzer's discoveries were, they would always be limited in scope. Both observatories are involved in multiple fields of investigation. What astronomers needed were spacecraft dedicated to planet discovery. This venture would come with the launch of Kepler, CORoT and the initiation of ground-based systems such as WASP in the ensuing years. Of these Kepler has certainly grabbed the largest share of attention, but all three ventures have revolutionized the field of planetary discovery.

Kepler was launched in 2009 after a 2-year delay. The Kepler telescope swung into position 1 million kilometers from Earth, in a heliocentric orbit, where the Sun and Earth's gravitational pulls are balanced. Without the erratic pull of Earth and the Moon the craft's cameras then focused with unique precision on star after star, detecting the subtle variations in starlight caused by transiting worlds.

With a steady gaze, Kepler has turned the science of planetary discovery into the banality of working in a cannery. A little harsh, perhaps, but effectively true. With its unblinking 0.95 m-wide eye, Kepler gazed at a small square of sky, filled with over 150,000 stars in a field 115 square degrees. Every minute of every hour, its sensitive CCD systems captured the subtle variations in stellar brightness caused by the ephemeral moths drawn to their eternal flames. Of course, the moth-candle analogy is a poor one. A moth fluttering in a car headlight, when the car is a kilometer away, might be a better descriptor. The variation in stellar luminosity caused by a planet transiting a Sun-like star is miniscule even when the planet is as large as Jupiter. Scale that along to see the effect of an Earth-sized world and you get the picture. The variation in stellar luminosity caused by an Earth-like world transiting a Sun-like star is as low as 80 parts in a million – barely above background noise. Thus confirmation of such diminutive worlds relies on data from multiple transits. Super-terrans – large terrestrial or water-dominated worlds, or their larger Jupiter-like relatives will clearly impose a more significant variation in the brightness of its star than a smaller world. However, it was initially unclear how commonplace such giant planets were around red dwarfs.

Despite the difficulty of the technique Kepler and a clutch of Earth-based transit observatories began to churn out planet after planet. After ruling out the effects of gravitational microlensing, star spots, flares and other ephemeral phenomena, astronomers were ready to claim a rather large prize: a vast toll of planets.

After less than 1 year of operation, Kepler had spied and confirmed the dimming effect of over 400 planets. Four hundred is a somewhat embarrassing figure – matching the number found by all other techniques in the preceding 15 years. That said, another 400 or so planets likely skulked in the data from other stars, awaiting further confirmation. Marvelous stuff, indeed.

For a long time planetary astronomy was the preserve of theory or of the study of the Sun's worlds. With Kepler, routine discovery has allowed a lot more science to be dissected and refined and the essence of true discovery to be made. Although Kepler grabs much of the media focus concerning planet discovery, WASP

(Wide-Angle Search for Planets) and France's CORoT (from the somewhat forced acronym COnvenction Rotation et Transits planétaires) have turned up a slew of interesting worlds.

WASP (or more accurately super-WASP) is an international collaboration based at the Roque de los Muchachos Observatory at La Palma in the Canaries and the South African Astronomical Observatory, with headquarters in Capetown. Utilizing a series of wide-angle lens cameras, and with observatories in two hemispheres, a whopping 500 square degrees of sky is covered, extending down to 15th magnitude objects. This allows for a very detailed and broad sweep of the heavens for transiting exoplanets.

Amongst, WASP's notable discoveries are a series of super-heated planets in tight orbits around their host Suns. WASP detected the hottest known exoplanet using the transit method. WASP-33b is a giant planet in an eccentric orbit around its F-class main sequence star. A combination of a tight orbit – at less than 7 % that of Mercury-Sun distance – and a relatively hot central star mean its cloud tops sizzle at over 3,000 °C.

More bizarre still is WASP-12b. Initially crowned as the hottest exoplanet, with cloud-top temperatures in excess of 2,200 °C, WASP-12b was shown to orbit its star so closely that tidal forces distort it into an egg shape. The combination of extreme heating and nose-touching proximity to its star means that this egg-shaped world is being steadily torn apart.

Although evaporating exo-Jupiters had already been spotted – the first, HD 209458b, by Hubble – WASP 12b was a different kind of beast. Whereas the massive HD 209458b would probably survive in some form for the duration of its star's main sequence life, WASP-12b was being shredded at such a rate that it probably wouldn't last much more than 10 million years. To observe the final fling of this planet's short remaining life might have been serendipity in the extreme, or perhaps more likely WASP-12b had suffered some form of interaction with another unseen world, which pulled it into an unstable orbit close to its host Sun. Whatever, the true reason, WASP12-b hasn't much time left. Within another 10 million years, all that will remain of the once-giant planet will be its spectral signature in the gases that make up the star's corona. Ashes to ashes.

However, the transit method has another use. It can detect other unseen worlds orbiting the same star. Where more than one planet is present the gravitational tug of the second, third or more planets will alter the period of time between transits of the known world. This method was successfully employed by WASP to infer the presence of planet WASP-3c, after close scrutiny of the transit times of the transiting world, WASP-3b. WASP-3c does not transit its star, but its presence can be known from the observed effect of WASP-3b. Moreover, where a distant planet orbits a pair of closely orbiting binary stars, the same principle can be applied, and variation in the intervals between eclipses can similarly be used to infer the presence of unseen planetary bodies.

Alongside WASP, CORoT has been diligently carrying out transit sweeps since 2007 and in essence paved much of the way for the later and heavily delayed Kepler mission of NASA. Not only did CORoT illustrate that the transit method was an efficient means of planet hunting, it also refined the extent of stellar variability in Sun-like and lower mass stars. This important function constrains a considerable fraction of the background noise, which might otherwise interfere with transit searches. The periodic dimming and brightening of a star caused by a transiting world can readily be mimicked by a star spot rotating in and out of view, or the effect of weak stellar pulsations. In this regard CORoT demonstrated that there was a greater than expected level of pulsation in many Sun-like stars; information that would then limit the ability of Kepler to carry out its task.

By 2011 CORoT had bagged around 600 planetary candidates, including the first found to show a secondary minimum in the light curve of the parent star (Fig. 1.3). This occurs as the illuminated planet (CORoT 1b) moves behind the parent star and the additional reflected light visible on Earth is lost behind the parent star. Capturing a secondary minimum is quite a feat, given the minuscule amount of light reflected from the orbiting planet.

In 2010 CORoT unveiled COROT-9b. This transiting planet was the first known to enjoy a temperate orbit around its host star. The relatively low mass of its orange, K-class host star (Chap. 3) means that the surface temperature of CORoT 9b lies somewhere between –20 and 160 °C. This is despite CORoT 9b orbiting at an equivalent distance to Mercury. At its time of discovery in 2010, the orbital separation of 0.36 A.U. was by far the largest of any transiting exoplanet from its star that had been observed.

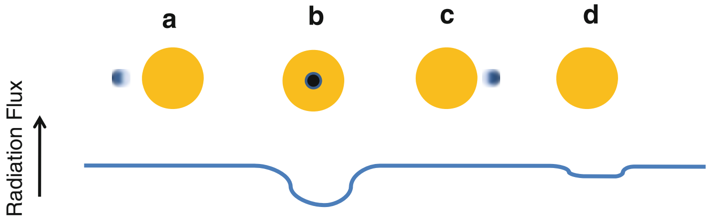

Fig. 1.3 The (exaggerated) effect of a transiting planet on the light curve of its parent star. As the planet moves in front of the star (*B*) the light is partially blocked, causing the star to appear to dim. This is what Kepler is looking for in its field of 150,000 stars. More rarely, a much shallower secondary minimum is detected (*D*) as the illuminated planet moves behind the star and less light is reflected in the direction of the observer. In reality the light curve will be more complex as the area of the planet illuminated by its star varies throughout its orbit. CORoT was the first craft to observe this effect with CORoT 1b

At the other extreme lies HD 14902b. This world was initially identified in 2005 in radial velocity data by the N2K Consortium. The consortium was a 2-year-long collaborative venture of Chilean, Japanese and U. S. astronomers to identify extrasolar planets using the radial velocity technique. The project focused on 2,000 nearby bright main sequence stars that were not already the focus of investigation in the astronomical community. Observations ran at Keck, Subaru and Magellan, plus an automated 'scope at the Fairborn Observatory, which looked for planetary transits.

The expectation was that around 60 planets would be found, but in the end only seven were confirmed. Of these HD 14902b was rather unusual. Each transit decreased the light from its host star by 0.003 magnitudes. This doesn't sound like much, but it was enough to allow the amateur astronomer Ron Bissinger to confirm it. Moreover it suggested that HD 14902b was a fairly large planet, close to its star. Once more the combination of data allowed a lot of detail to be gleamed concerning this odd world. The concomitant identification by an amateur astronomer using a backyard 'scope equipped with its own CCD array opened the door of planet discovery to the amateur astronomy community in general – a huge achievement.

Despite being yet another hot Jupiter, HD 14902b stands out in that it is extremely dense. More than three-quarters of its 114 Earth-mass bulk is rock and metal – a whopping 80–110 Earth-masses.