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978-1-108-41977-2 — The Exoplanet Handbook
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Excerpt
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Introduction

1.1 The challenge

There are hundreds of billions of galaxies in the observable Universe, with each galaxy such as our own containing some hundred billion stars. Surrounded by this seemingly limitless ocean of stars, mankind has long speculated about the existence of planetary systems other than our own, and the possibility of life existing elsewhere in the Universe.

Only recently has evidence become available to begin to distinguish the extremes of thinking that has pervaded for more than 2000 years, with opinions ranging from *'There are infinite worlds both like and unlike this world of ours'* (Epicurus, 341–270 BCE) to *'There cannot be more worlds than one'* (Aristotle, 384–322 BCE).

Shining by reflected starlight, exoplanets comparable to solar system planets will be billions of times fainter than their host stars and, depending on their distance, at angular separations from their accompanying star of, at most, a few seconds of arc. This combination makes direct detection extraordinarily demanding, particularly at optical wavelengths where the star/planet intensity ratio is large, and especially from the ground given the perturbing effect of the Earth's atmosphere.

Alternative detection methods, based on dynamical perturbation of the star by the orbiting planet, delivered the first tangible results around 1990. Radio pulsar timing achieved the first convincing detection of planetary mass bodies beyond the solar system (Wolszczan & Frail, 1992). High-accuracy radial velocity (Doppler) measurements yielded the first suggestions of planetary-mass objects surrounding main sequence stars from the late 1980s (Campbell et al., 1988; Latham et al., 1989; Hatzes & Cochran, 1993), with the first essentially unambiguous detection in 1995 (Mayor & Queloz, 1995).

Progress since 1995 This discovery precipitated a changing mindset. The search for exoplanets, and their characterisation, rapidly became a respectable domain for scientific research, and one equally quickly supported by funding authorities. More planets were discovered by radial velocity search teams in the following years. In 1998, the technique of gravitational microlensing provided evidence for a low-mass planet orbiting a star near the centre of the Galaxy nearly 30 000 light-years away, with the first confirmed microlensing planet reported in 2004. In the photometric search for transiting exoplanets, the first transit of a previously-detected exoplanet was reported in 1999, the first *discovery* by transit photometry in 2003, the first of the wide-field bright star survey discoveries in 2004, and the first discovery from space observations in 2008.

While these manifestations of the existence of exoplanets are also extremely subtle, advances in Doppler measurements, photometry, microlensing, timing, imaging, and astrometry, have since provided the tools for their detection in relatively large numbers. Now, almost 25 years after the first observational confirmation, exoplanet detection and characterisation, and advances in the theoretical understanding of their formation and evolution, are moving rapidly on many fronts.

1.2 Discovery status

As of the end of 2017, more than 3500 confirmed planets were known, with some 600 multiple systems. Some statistics, according to discovery method, are listed in Table 1.1. An observational chronology, of necessity both selective and subjective, is given in Table 1.2.

Diversity Continuing the trend established by the earliest discoveries, exoplanets do not adhere to the individual or system properties extrapolated from the known architecture of the solar system.

Orbital properties vary widely. Many have very elliptical orbits, $e \gtrsim 0.3$, compared to the largest eccentricities in the solar system of ~0.2 for Mercury and Pluto (and 0.05 for Jupiter). Of planets with estimated masses, some half are around that of Jupiter ($0.3 - 3M_\mathrm{J}$), and a number of these orbit their host star much closer than Mercury orbits the Sun (0.39 au): hot highly-irradiated giants piled up towards 0.03 au that are unlikely to have formed *in situ*. Others are located far out, at distances of 100 au or more from their host star. Orbits highly inclined to the star's equatorial plane occur reasonably frequently, some even with retrograde orbits.

Table 1.1: Exoplanet discovery statistics, from the NASA Exoplanet Archive, 2017 December 31. The table has some simplifications. For example, systems can be multiple with one or more planets discovered through transit measurements, and others in the system discovered by radial velocity follow-up. Some planets designated in the NASA Exoplanet Archive as detected by 'timing' were the result of transit timing measurements.

Category	Chapter	Systems	Multiple	Planets
Detections				
Radial velocity	2	504	102	662
Astrometry	3	1	0	1
Timing	4	20	5	32
Microlensing	5	51	2	53
Transits	6	2053	474	2789
Imaging	7	40	2	44
Total				3572

Exoplanets are being discovered around a wide variety of stellar types. Host stars are not only main sequence stars like the Sun, but they include very low-mass stars, low metallicity stars, giant stars, and other advanced evolutionary stages such as white dwarfs and pulsars. Their internal structure and composition vary widely too. Gas giants with stripped outer envelopes, water worlds formed beyond the snow line, and carbon-dominated terrestrial planets may all exist. Exoplanet atmospheres are being probed through transit and secondary eclipse photometry and spectroscopy.

In multi-planet systems, many planets orbit in, or close to, mean motion resonance, presenting a certain challenge to explain their occurrence. Triple-planet Laplace resonances and complex resonance chains have been discovered, as have prominent transit timing variations in multi-planet transiting systems. Systems with low-mass planets are being found in increasing numbers as the radial velocity surveys improve their detection threshold and increase their temporal baseline. High-order multiple systems are being found both from radial velocity and transit surveys, with one known 8-planet transiting system (Kepler–90), one 7-planet transiting system (TRAPPIST–1), and six 6-planet (radial velocity and transiting) systems.

Frequency Based on present knowledge from the radial velocity surveys, at least 5–10% of solar-type stars in the solar neighbourhood harbour massive planets. A much higher fraction, perhaps 30% or more, may have planets of lower mass or with larger orbital radii. If these numbers can be extrapolated, the planets in our Galaxy alone would number many billions.

1.3 Outline of the treatment

The present volume summarises the main areas of exoplanet research, combining a description of techniques, concepts, and underlying physics, with a review of the associated literature through to the end of 2017.

It is formulated as an overview of all aspects of exoplanet research, intended to be accessible to both astronomers and planetary scientists, emphasising the interconnection between the various fields of investigation, and providing extensive pointers to more in-depth treatments and reviews.

1.3.1 Observational techniques

Chapters 2–7 divide the search for and characterisation of exoplanets according to detection technique. In each case, the underlying principles are summarised, along with the principal instruments in use, the status of experimental results, and the instrumentation planned for the future. Figure 1.1 summarises the various detection techniques that are the subject of these chapters. Figures 1.2–1.3 show the discoveries with time in the form of the development as a function of semi-major axis, and as simple histograms, respectively.

Radial velocity Chapter 2 covers the many aspects of radial velocity (Doppler) measurements, including the instrumental approaches being used and under development. It starts with a treatment of planetary orbits, indicating how radial velocity measurements (as well as astrometry, independently and together) provide access to the planet's orbital parameters. The text covers the basics of wavelength calibration, the contributory error sources, and an overview of the latest results from Doppler searches, including those around binary and multiple stars. The development of sub-1 $\mathrm{m\,s^{-1}}$-class accuracies is resulting in the detection of low-mass planets down to just a few Earth masses, which are beginning to appear in large numbers, in multiple systems, and at separations corresponding to the 'habitable zone'.

Astrometry Chapter 3 covers the principles of the detection and characterisation of planetary orbits by astrometric measurement. The limiting factors for ground-based and space-based instruments are summarised. Since the largest astrometric displacements expected for the most massive nearby planets amount to of order 1 milliarcsec, below that detectable from ground, and comparable to the state-of-the art from space with Hipparcos and HST–FGS, few planets can yet be confirmed through their astrometric displacements, and only one claimed discovery has been by astrometry alone. The panorama of astrometric discovery and characterisation is changing substantially, as this volume goes to press, with the advent of microarcsec accuracies from the space astrometry mission Gaia.

Timing Chapter 4 covers exoplanet detection by the measurement of orbit timing residuals, the third discovery technique which makes use of the reflex dynamical motion of the host star. The first non-solar system objects of planetary mass were detected by this technique

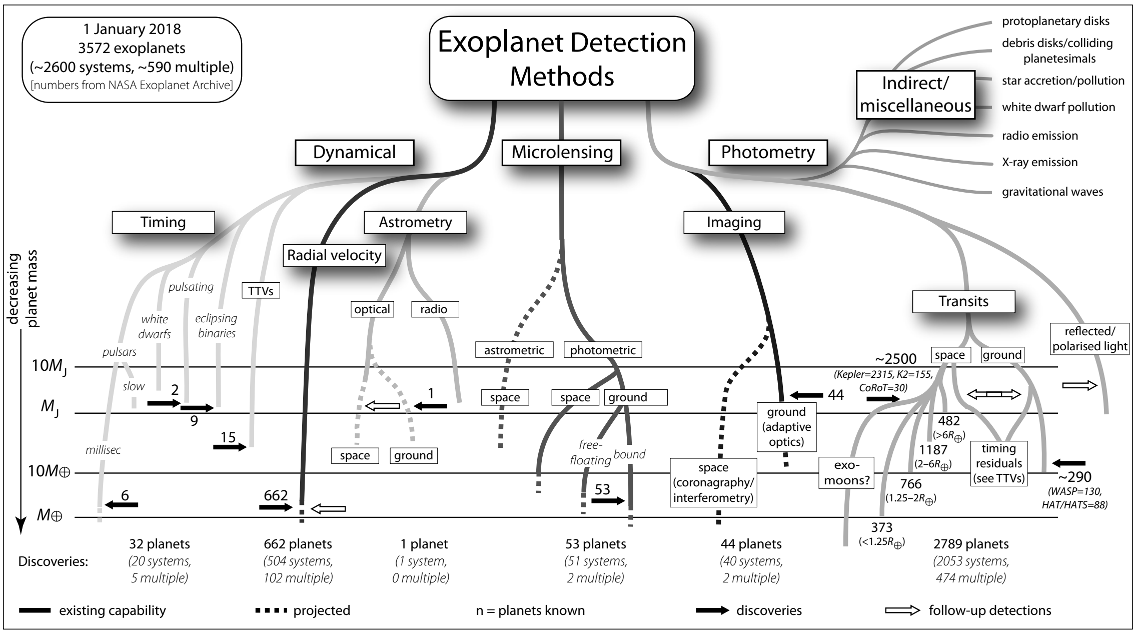

Figure 1.1: Exoplanet detection methods. The lower limits of the lines indicate masses within reach of present measurements (solid lines), and those that might be expected within the next few years (dashed). The (logarithmic) mass scale is shown at left. Miscellaneous signatures to the upper right are less well quantified in mass terms. Solid arrows show relevant discoveries. Open arrows indicate measurements of previously-detected systems. Numbers are from the NASA Exoplanet Archive, 2018 January 1.

using radio pulsar timing in 1991–92. Although pulsars with planets remain the exception, the same technique is being applied to stars which have an underlying periodic photometric signature which is then modulated by an orbiting planet. The technique has been applied to detect planets around pulsating white dwarfs, pulsating subdwarfs, and eclipsing binaries. Its success has underlined the diversity of stellar types around which planets remain in orbit.

Microlensing Chapter 5 covers detection by gravitational microlensing. While sampling primarily rather distant systems, its main disadvantage is that it can only provide a single measurement epoch spanning hours or days. A noteworthy milestone was the measurement, reported in 2008, of a 2-planet system in which orbital motion could be measured during the 10-day event duration. The ability to detect true free-floating planets, a sensitivity to Earth-mass planets in the habitable zone and beyond, and a technique independent of the host star spectral type or luminosity class, make the prospects of a space-based microlensing survey of particular importance to a broad exoplanet survey census.

Photometry and transits Chapter 6 covers photometric measurements, most importantly the search for exoplanets transiting the disk of their host star, as well as searches for reflected and polarised light. Whilst transits only occur for planets whose orbits happen to lie essentially orthogonal to the plane of the sky, this constrained geometry allows both the radius of the planet to be determined (at least in terms of the stellar radius), of major importance for exoplanet characterisation, and (under certain assumptions) its mass. Together yielding the exoplanet density, this offers the first insights into the internal structure and chemical composition of the transiting planet. The search for transit time and transit duration variations offers prospects for detecting accompanying members of the planetary system. Important insights into planet atmospheres are being obtained from transit and secondary eclipse spectroscopy.

Transit techniques, and discoveries, have been revolutionised by the Kepler mission, launched in 2009. It has discovered more than 2000 confirmed planets, and searched for other (potentially) transiting bodies, including comets, rings, exomoons, and tidally-disrupted planets. It has identified a wide range of physical effects such as spin–orbit misalignments, apsidal and nodal precession, and planet–planet eclipses, with insights into statistical properties such as co-planarity, multiplicity, resonances, and dynamical packing.

Direct imaging Chapter 7 covers the techniques in use and under development for the direct imaging of an exoplanet in orbit around its host star. The technical challenges, and technological solutions (adaptive optics, coronagraphy, and space-based imaging and interfer-

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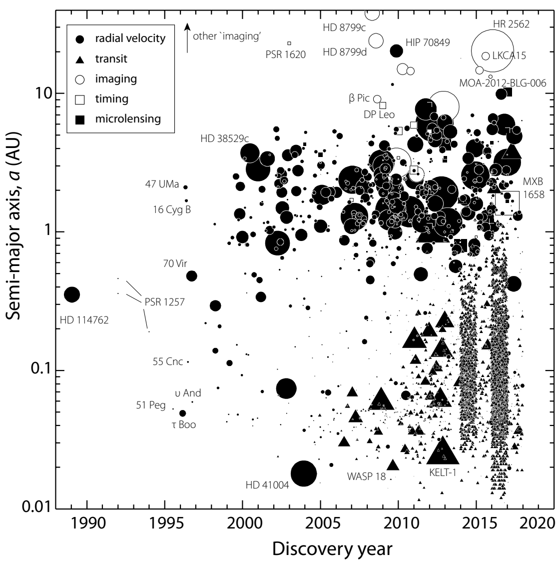

Figure 1.2: Exoplanet discoveries versus year, with content from the NASA Exoplanet Archive as of 2017 December 31. Symbols indicate the discovery method (timing and pulsar planets are taken together, and all Kepler discoveries are taken as 'transit' discoveries). If semi-major axes, a, were not listed, they were estimated from P and $M_\star$ (Equation 2.17). Symbol sizes are proportional to $M_{\rm p}$, with the largest $\sim 20-30 M_{\rm J}$ and the smallest to $0.2 M_{\rm J}$ or less. Kepler planets without $M_{\rm p}$ are shown with small symbols. Scatter within any given discovery year is randomised. The two prominent vertical (Kepler) bands reflect the announcement dates. A few planets are labeled. HD 114762 is a later confirmation of the earlier tentative discovery.

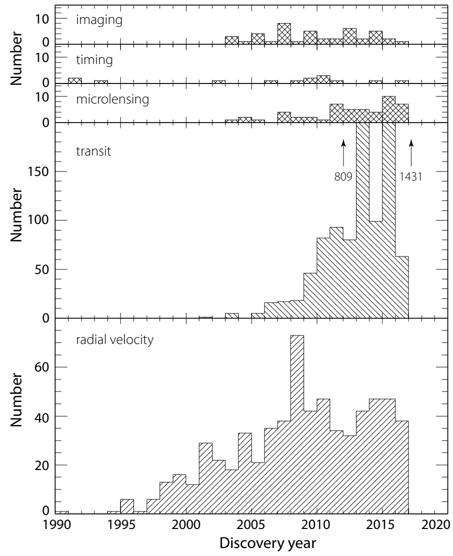

Figure 1.3: Exoplanet discoveries versus year, and detection method, with content from the NASA Exoplanet Archive as of 2017 December 31. The large numbers of Kepler transiting planets announced in 2014 and 2016 are off scale.

ometry) are described, along with the results obtained to date, including with advanced newly-commissioned second-generation imaging instruments. This chapter also covers prospects for direct detection based on magnetospheric radio emission, as well as observations at mm/sub-mm wavelength.

1.3.2 Host star properties and brown dwarfs

Host stars Chapter 8 reviews the properties of exoplanet host stars. It includes discussion of their Galactic orbits, their axial rotation, their elemental abundances, and the theories put forward to explain the observed correlation between the occurrence of exoplanets and host-star metallicity. It reviews asteroseismology investigations that have been carried out on a number of host stars, the range of star–planet interactions including characteristics of their X-ray emission, and the inferences being made from white dwarf photospheres.

Brown dwarfs Chapter 9 provides an overview of the properties of brown dwarfs. The subject overlaps with that of exoplanets both in the definition of a planet, and in the context of so-called free-floating objects of planetary mass which have been discovered in nearby young star-forming regions.

1.3.3 Theoretical considerations

Chapters 10–11 deal with the theories of formation and evolution, and of their interiors and atmospheres.

Formation and evolution Chapter 10 is a summary of the present understanding of planet formation and evolution. Very broadly, the current picture is that formation started with a collapsing protostellar disk, with planets assembled from dust and gas by the progressive agglomeration of material over some 14 orders of magnitude in size. The gas and ice giants, of masses $\gtrsim 10 M_\oplus$, formed by either, perhaps both, core accretion or gravitational disk instability. Close-in planets, high eccentricities, and orbital resonances provide evidence for planetary migration subsequent to formation. Inward, and sometimes, outward migration as a result of interactions between the planet and the gas and residual planetesimal disk, along with planet–planet scattering, provides a compelling picture of the diversity of planetary system architectures observed. For planets that arrive to within ~0.2 au of the host star, whether by migration or scattering, tidal effects become significant, circularising orbits, synchronising their rotation and orbital periods, and providing an additional source of internal heating.

Interiors and atmospheres Chapter 11 reviews the current knowledge of interiors and atmospheres, deduced primarily from the masses and densities measured for transiting planets, combined with theoretical models based on the equations of hydrostatic and thermodynamic equilibrium. Thermal equilibrium and condensation calculations can predict which chemical species will be present for a given initial elemental composition and, from these, insight is being gained into their internal structures and atmospheric compositions.

For terrestrial-mass planets, estimates of the habitable zone, where liquid water could be present, are providing pointers to the first planets which may be habitable. The chapter includes some details of spectroscopic indicators of life, the ongoing search for extraterrestrial intelligence, and related aspects such as the Anthropic Principle and the Fermi Paradox.

1.3.4 Solar system

Chapter 12 provides a selective summary of solar system properties which are closely linked to developments in exoplanet studies. Solar system observations provide important constraints on theories and properties of exoplanet formation and evolution, while developments in exoplanet formation and evolution, notably planetary migration, are offering insight into the present structure and past evolution of the solar system.

Topics covered include relevant properties of the Sun, orbital stability and planet obliquities, the origin of the Moon, of water on Earth, and of planetary satellites and rings, and the current theories of planet migration believed to have occurred in the early solar system. Taken together, combined knowledge of exoplanets and the solar system is providing an increasingly detailed picture of planet formation and evolution, further suggesting that the basic models of exoplanet formation, and that of the solar system, are broadly coherent.

1.3.5 Appendixes

Appendix A is a compilation of numerical values of relevant reference quantities. Appendix B is a summary of the principle notation used throughout the treatment. While the use of acronyms has been avoided where possible, a list of those commonly encountered in the associated literature is included.

Appendixes C–F provide a bibliography of the main classes of exoplanet detections (radial velocity, transiting, microlensing, and imaging respectively), with a brief narrative of each system and the associated literature. These aim to provide a concise picture of the main lines of research associated with each planetary systems.

1.3.6 Hyperlinks and online resources

The electronic (PDF) version is extensively hyperlinked although, to enhance legibility, links are not explicitly visible. Principal links are those in the table of contents, to sections, tables, figures, equations, and citations.

Citations within the text are hyperlinked to the relevant *page* of the reference bibliography. Within the bibliography, each bibliographic entry is in turn hyperlinked to the relevant ADS abstract page. In the few instances where the ADS does not include the relevant citation link (typically older or non-astronomical articles) the link points only to the ADS search page.

The reference bibliography also includes 'back references', linking the bibliographic item to the page(s) on which the reference was cited. These back references are also actively hyperlinked to the relevant cited page(s).

In the planet chronologies, Appendixes C–F, the host star name is hyperlinked to the host star page of the NASA Exoplanet Archive. In addition to hyperlinks to the reference bibliography, the ▹ icon *following* the citation leads directly to the relevant ADS abstract page.

As detailed in the Preface, a number of files are available at `www.cambridge.org/exoplanethandbook`.

1.4 Astronomical terms and units

A summary of key astronomical terms and nomenclature is provided for those with less familiarity of the field.

Astronomical terms Various relevant terms used in astronomy and planetary science may cause some confusion on first encounter. More detailed explanations are given in appropriate places in the text, but advanced warning of some of these may assist orientation.

Metallicity: in astronomy usage, the term 'metal' is divorced from its usual chemical definition related to electrical conductivity and chemical bonding, and instead refers collectively to all elements other than H or He (and essentially therefore to the elements produced by nucleosynthesis in stars or supernovae).

Ice, gas, and rock: in planetary science, 'ices' refer to volatile materials with a melting point between ~100–200 K. In consequence, 'ices' (for example in Uranus and Neptune) are not necessarily H_2O, not necessarily 'cold', and not necessarily solid. Similarly, a 'gas' in planetary science is not defined by phase, but rather as a highly volatile material with a melting point (if at all) below ~100 K. 'Rock' may be defined by its solid phase or present mineralogical composition, but generally also by its presumed chemical composition and highly refractory nature during the epoch of planetary formation.

Notation for star and planet parameters Stars and planets are characterised, amongst other parameters, by their mass M and radius R, with subscripts $\star$ and p referring to star and planet respectively, and the distance to the system d.

Masses and radii of stars are usually expressed in solar units ($M_\odot, R_\odot$), while those of planets are typically expressed in either Jupiter units (M_J, R_J) for the more massive, or Earth units ($M_\oplus, R_\oplus$) for planets closer to terrestrial mass. Numerical values (and sources) for these and other quantities are given in Appendix A.

Orbits are primarily characterised by their period P, semi-major axis a, eccentricity e, and inclination with respect to the plane of the sky i ($i = 0°$ face-on, $i = 90°$ edge-on). Further details are given in §2.1.1.

Nominal conversion constants Given that neither the solar nor the planetary masses and radii are secularly constant, and that their instantaneous values are being determined ever more precisely, IAU (2015) Resolution B3 recommended nominal conversion constants for selected solar and planetary (Earth/Jupiter) properties (Mamajek et al., 2015b). The motivation is that their consistent use in relevant formulae and models (and employing the recommended notation which, however, is not used here), would guarantee a uniform conversion to SI units. These recommended values are consistent with the solar system ephemerides values in Appendix A, and with the IAU 2009 system of astronomical constants (Luzum et al., 2011).

Thus the IAU nominal (N) equatorial (e) and polar (p) radii for Earth and Jupiter (at a pressure of 1 bar ≡ 10^5 Pa) are

$$1\mathscr{R}^{\rm N}_{\rm eE} = 6.3781 \times 10^6\,{\rm m} \qquad 1\mathscr{R}^{\rm N}_{\rm pE} = 6.3568 \times 10^6\,{\rm m} \tag{1.1}$$

$$1\mathscr{R}^{\rm N}_{\rm eJ} = 7.1492 \times 10^7\,{\rm m} \qquad 1\mathscr{R}^{\rm N}_{\rm pJ} = 6.6854 \times 10^7\,{\rm m} \tag{1.2}$$

If the equatorial or polar radius is not explicitly specified, the former is to be understood. The *de facto* definition of $R_{\rm J}$ in terms of Jupiter's *equatorial* radius at 10^5 Pa means that, due to its oblateness, Jupiter's *mean* radius is actually $0.978R_{\rm J}$.

Star distances and masses Stellar distances are given in *parsec* (pc). As the basic unit of astronomical distance based on measurements of trigonometric parallax, this is the distance at which the mean Sun–Earth distance (the astronomical unit, or au; Appendix A) subtends an angle of 1 arcsec (1 pc ≃ 3.1 × 10^{16} m ≃ 3.26 light-years).

For orientation, distances to the nearest stars are of order 1 pc; there are about 2000 known stars within 25 pc of the Sun. With the exception of microlensing events, most exoplanet discoveries and detections are restricted to a distance horizon of order 50–100 pc.

In general, stellar masses range from $\sim 0.1 - 30\,M_\odot$, with spectral types providing a conventional classification related to the primary stellar properties of temperature and luminosity. The Sun is of spectral type G2V, with a main-sequence (H-burning) life time around 9 Gyr: cooler stars (types K, M) are of lower mass and have longer lifetimes; hotter stars (types F, A, etc.) are of higher mass and have shorter lifetimes. Stellar masses of interest to exoplanet studies are typically in the range $0.1 - 5\,M_\odot$, with the majority of targets and detections focused on masses rather close to $1\,M_\odot$.

Star names Details of the naming conventions of celestial objects, ratified by the IAU Commission 5 Working Group on Designations, are given at the URL in Table 1.4.

Object names such as 70 Vir (for 70 Virginis) and β Pic (for β Pictoris) reflect constellation-based nomenclature, while others reflect catalogues or techniques labeled with running numbers (e.g. HD 114762) or coordinates (e.g. PSR B1257+12). Some of the most commonly referenced star catalogues of relevance are:

HD (Henry Draper): surveyed by Cannon & Pickering (Ann. Astr. Obs. Harvard, Vol. 91–99, 1918–1924).

HIP (Hipparcos): the space-based astrometric catalogue extends to ≃ 12 mag, but with a completeness between 7.3–9.0 mag depending on Galactic latitude and spectral type (Perryman et al., 1997a, see §8.1.1).

BD (Bonner Durchmusterung): the BD was the first of the 3-part Durchmusterung (German for survey) covering the entire sky. The northern sky was surveyed from Bonn by Argelander & Schönfeld and published between 1852–1859. The extension southwards was surveyed from Córdoba, Argentina (Córdoba Durchmusterung, or CD) by Thomme starting in 1892. The southern skies were surveyed from the Cape of Good Hope (Cape Durchmusterung, or CPD) by Gill & Kapteyn around 1900. Stars tend to be assigned their DM (Durchmustering) number if they are not in the HD or HIP catalogues.

Nearby stars: if included in the Catalogue of Nearby Stars (CNS; §8.1.3), they are designated in the CDS SIMBAD database as GJ nnn. The deprecated alternatives Gliese nnn or Gl nnn are sometimes encountered.

Alternative designations: alternative exoplanet host star designations are often encountered, especially until some consensus designation has been adopted. Thus some early studies referred to 55 Cnc as HR 3522 or ρ^1 Cnc; HIP 75458 as ι Dra or HD 137759; HR 810 as ι Hor or HD 17051; etc. The CDS SIMBAD facility (Table 1.4) provides full cross-identifications.

Exoplanet names: Various alternative naming schemes have been proposed, none having gained wider support.

A few planets have been given unofficial epithets (by their discoverers or others): Bellerophon ≡ 51 Peg b (Lyra, 2010); Osiris ≡ HD 209458 b (Vidal-Madjar et al., 2008); Tatooine ≡ Kepler–16(AB) b (the fictional planet orbiting two suns in Star Wars); Zarmina ≡ GJ 581 g (Vogt et al., 2010a); Methuselah ≡ PSR B1620–26 b (for its extreme age); and Einstein's planet ≡ Kepler–76 b (Faigler et al., 2013).

Lyra (2010) proposed constellation-based names mostly drawn from Roman–Greek mythology for the 403 planets known in October 2009; those in Pegasus included Bellerophon (51 Peg b), Minerva (HD 209458 b), Nike (HAT–P–8 b), and Parthenos (WASP–10 b).

A more quantitative 4-parameter taxonomic classification, intended to be easily interpreted whilst conveying the most relevant planetary information, was proposed by Plávalová (2012). It qualifies planet mass in terms of solar system masses (m/E/N/J), logarithmic semi-major axis, mean temperature [F(reezing), W(ater), G(aseous), R(oaster), and P(ulsar)], and orbital eccentricity.

The International Astronomical Union (IAU) originally stated that it had no plans to assign names to extrasolar planets, considering that *'if planets are found to occur very frequently in the Universe, a system of individual names might well rapidly be found impracticable'*. Nonetheless, in July 2014, it initiated a process to assign names to certain systems, via public nomination (`www.iau.org/public/themes/naming_exoplanets`). In December 2015, for example, the IAU announced the winning names for the PSR B1257+12 pulsar system: Lich for the pulsar, with Draugr, Poltergeist and Phobetor for its planets.

Other commercially-oriented naming websites exist.

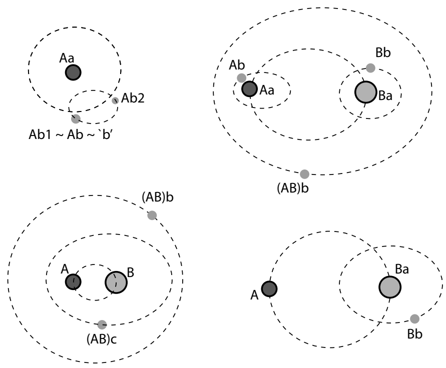

Figure 1.4: Exoplanet name suffixes for single and binary systems following Hessman et al. (2010). Upper left: planet around a single star plus a moon. Upper right: binary star, each with a planet (e.g. HD 41004), plus a circumbinary planet. Lower left: two circumbinary planets (e.g. NN Ser). Lower right: planet around the secondary star in a binary (e.g. HD 178911). From Hessman et al. (2010, Figure 1).

Coordinate designation: coordinate-based designations for (typically fainter) sources from catalogues such as 2MASS and SDSS are detailed on page 432.

Kepler targets: Kepler mission targets may be referred to by their confirmed Kepler–NNN identifier, or by their KIC or KOI identifiers, depending on validation status (box, page 175). This work adopts the Kepler–NNN identifier where assigned. The NASA Exoplanet Archive (Table 1.4) provides cross-identifications, along with the default identifier.

Exoplanet identifiers The *de facto* custom denotes planets around star X as X b, c,... lexically according to discovery sequence (rather than, for example, according to mass or semi-major axis, which would demand constant revision as additional planets are discovered).

Nomenclature for planets in binary star systems, following Hessman et al. (2010), is illustrated in Figure 1.4.

The convention for microlensing planets, where the host star is generally invisible, is described on page 142.

Exomoon identifiers If and when exomoons are discovered, they are likely to be designated with post-fixed Roman numerals, following the convention for solar system satellites (cf. box, page 689). This has already been adopted for the exomoon candidate Kepler–1625 b I, identified by Teachey et al. (2018).

Units In aiming for a consistent usage of terms and nomenclature, units referred to in the published literature have occasionally been unified. Usage here follows, as far as is considered reasonable, the International System of Units (SI), including the SI prefixes for multiples of 10^3, 10^6 and 10^9 as k, M, and G.

Astronomical measures of density generally use the non-SI unit of $\mathrm{g\,cm^{-3}}$. Densities here are expressed in units of $\mathrm{Mg\,m^{-3}}$, conforming to SI, and with the same numerical values (and same number of keystrokes).

Characterisation of pressure, notably in the description of planetary atmospheres and interiors, is divided in the literature between the SI pascal, $1\,\mathrm{Pa} \equiv 1\,\mathrm{N\,m^{-2}}$, and the bar ($1\,\mathrm{bar} \equiv 10^5\,\mathrm{Pa}$). The latter, some 1% smaller than 'standard' atmospheric pressure, is not an SI unit, although it is accepted for use within SI. For uniformity, Pa is used preferentially here.

Various units outside of SI are accepted for use, or are consistent with the recommendations of the International Committee for Weights and Measures (CIPM, *Comité International des Poids et Mesures*). These include the measurements of time as minute (min), hour (h), and day (d), and the measurement of angles in seconds of arc: units of arcsec, mas (milli-arcsec) and μas (micro-arcsec) are used accordingly.

The IAU (1989) system of astronomical constants recommended the symbol 'a' for Julian year. This treatment follows wider astronomical convention in using 'yr' when the distinction of Julian year is unwarranted.

Specification of geological time (Chapter 12) faces the issue that, with SI adherence being less critical, a distinction is nonetheless often useful between geohistorical *duration*, and geohistorical *date*. This treatment follows the widespread (and recommended, Aubry et al., 2009) practice in geological science of expressing durations in years, symbol 'yr' (with multiples kyr, Myr, and Gyr); with dates (in years before present, or BP) denoted as 'annus', symbol 'a' (with multiples ka, Ma, and Ga).

Certain units central to astronomy, notably those of mass and radius noted above, deviate from SI, but are retained in this treatment. The astronomical unit is accepted within the SI; following the IAU (2012) recommendation, it is indicated here as 'au'.

A, AU, ua, au The IAU (1976) system of astronomical units used the symbol 'A' for the astronomical unit. In 2006, the International Bureau of Weights and Measures (BIPM), which reports to the CIPM, recommended use of 'ua', which was followed in the non-normative Annex C to ISO 80000–3 (2006). However, 'AU' continued as a common abbreviation. In 2012, the IAU recommended the use of 'au'. This was adopted in the BIPM's 2014 revision of the SI Brochure, and since by the major journals.

Mathematical notation A compilation of the adopted notation is given in Appendix B. For the designation of parallax, the symbol ϖ is widely used in the astrometric literature and is employed here (rather than the frequently used π), to avoid confusion with the mathematical constant with which it frequently appears.

North, south, east, west, morning, evening These terms, used in the context of atmospheric 'general circulation models' (§11.4.2), merit some explanation.

Earth's north pole being so denoted by convention, and its orbit about the Sun being prograde (in the same sense as its rotation), it rotates counter-clockwise when viewed from above its north pole. Its rotation from west to east, with the morning Sun perceived to 'rise' in the east, defines these concepts.

On Earth, winds termed 'easterly' or 'westerly' conventionally designate the direction from which they originate, viz. 'easterly' when they blow *from* the east (i.e. towards the west, or *westward*), and *vice versa* (although in other contexts, and potentially confusingly, reference may be made to an 'easterly' or 'westerly' *direction*). Earth's atmospheric circulation is characterised by prevailing equatorial *easterly* winds (box, page 594), while highly irradiated hot Jupiters are generally distinguished by equatorial prograde (westerly) winds, carrying energy from stellar irradiation *eastward* from the sub-stellar point, thereby signifying an atmosphere which is 'superrotating' (§11.4.2).

For other solar system bodies, the IAU Working Group on Cartographic Coordinates and Rotational Elements defines the geographic north pole of a planet (or satellite) as that in the same celestial hemisphere relative to the solar system's invariable plane as Earth's north pole (Archinal et al., 2011). An object's direction of rotation is then termed positive (prograde) if it rotates counter-clockwise when viewed from above its north pole, and negative (retrograde) if it rotates clockwise.

Compounded by the large inclination of the ecliptic, the IAU Working Group extends its definition to cases (e.g. Uranus) where the declination of a pole relative to Earth's celestial equator could be negative, even though a planet's north pole is north of the invariable plane; and to some minor bodies (e.g. comet 2P/Encke) where the poles precess rapidly enough to reverse over a few decades using the invariable plane definition.

Planetary *coordinate systems* are defined relative to their mean axis of rotation. The longitude systems of most solar system bodies with observable rigid surfaces are defined by reference to some surface feature, such as a crater.

For exoplanets, east and west are similarly defined in terms of an (assumed) prograde rotation (defined in terms of sidereal rotation for a tidally locked planet). As a result, even though hot Jupiters are spatially unresolved, a peak brightness generally observed to be temporally in advance of the secondary eclipse implies an *eastward*-shifted hot spot. Given such advected heat flow, the western terminator (dividing day- and night-sides) is also frequently referred to as the 'dawn terminator', or 'morning side' (being cooler), while the eastern terminator is also referred to as the 'dusk' or 'evening' terminator (being hotter).

1.5 Definition of a planet

Background: IAU 2003 recommendation The IAU 2003 recommendation, by the working group on extrasolar planets (IAU, 2003) is, verbatim:

(1) objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be $13M_\mathrm{J}$ for objects of solar metallicity) that orbit stars or stellar remnants are *planets* (no matter how they formed). The minimum mass required for an extrasolar object to be considered a planet should be the same as that used in the solar system;

(2) substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are *brown dwarfs*, no matter how they formed nor where they are located;

(3) free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not planets, but are *sub-brown dwarfs* (or whatever name is most appropriate).

Background: IAU 2006 resolution In its resolution B5 (IAU, 2006), the IAU classified the solar system bodies into three distinct categories (verbatim):

(1) a *planet* is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit;

(2) a *dwarf planet* is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite;

(3) other objects except satellites orbiting the Sun are referred to collectively as *small solar system bodies*.

This classification, which excludes Pluto as a planet under criterion 1(c), is nevertheless recognised as being somewhat ambiguous due to the difficulties in formulating precise definitions of shape and orbital 'clearing'.

Adopted convention Attempts to formulate a precise definition of a planet are confronted by a number of difficulties (e.g. Basri & Brown, 2006). At the upper mass range, definitions according to formation scenario, or according to mass, encounter problems if these two definitions do not coincide. Chabrier et al. (2014) argued that the IAU definition for distinguishing planets from brown dwarfs on the basis of deuterium burning *'has no physical justification and results in scientific confusion'*. At the lower mass range, classification is presently facilitated by the fact that a distinction in mass between exoplanets and smaller bodies is not yet relevant.

A definition dispensing with upper and lower mass limits is suggested by Soter (2006): *A planet is an end product of disk accretion around a primary star or substar*. In this case, the upper mass limit for a planet is probably in the range $25-30M_\mathrm{J}$, rather than $13M_\mathrm{J}$. There is presumably no reason why a 'planet' could not form in this way, and burn its deuterium. Indeed, Schneider et al. (2011) assigned a mass of $25M_\mathrm{J}$ as the upper limit for including objects in the Exoplanet Encyclopaedia. An illustrative case is the 2-planet system HD 168443 (Marcy et al., 1999, 2001b; Udry et al., 2002; Pilyavsky et al., 2011), in which planet b ($M_\mathrm{p}\sin i = 8.2M_\mathrm{J}$) and planet c ($M_\mathrm{p}\sin i = 18.1M_\mathrm{J}$) lie below and above the deuterium-burning threshold respectively, but presumably have a common (disk-accretion) origin.

Hatzes & Rauer (2015) proposed a definition based on changes in slope of the $\log M$–$\log\rho$ relation (§11.5.4). By this criterion, objects with $M_\mathrm{p} \lesssim 0.3M_\mathrm{J}$ are low mass planets, either icy or rocky. Giant planets cover the range $0.3-60M_\mathrm{J}$, with objects of a few M_J considered as 'low mass giant planets', while those at the upper end of the giant planet sequence (brown dwarfs) referred to as 'high mass giant planets'.

In this treatment, isolated objects are referred to as sub-brown dwarfs or brown dwarfs according to whether they lie below or above the deuterium-burning threshold, and (generally) only as 'free-floating planets' if evidence suggests that such a label is appropriate.

1.6 Planet categories

With more than 3500 planets known by the end of 2017, various attempts have been made to classify them. This section provides an introduction to the classes of planets being discovered, in anticipation of the following discussions of their discovery and theories of their formation.

1.6.1 Classification by size or mass

Planet size As detailed in Chapter 6, the key observable for transiting planets is its (relative) size (rather than mass). Borucki et al. (2011b) adopted the categories:
- Earth-size, or terrestrial planets ($< 1.25R_\oplus$),
- super-Earth-size ($1.25 - 2R_\oplus$),
- Neptune-size ($2 - 6R_\oplus$), and
- Jupiter-size ($6 - 15R_\oplus$).

These are not universally-accepted 'definitions', and other boundaries have been adopted (e.g. Morbidelli & Raymond (2016) consider super-Earths as $R_p < 4R_\oplus$ and $P < 100$ d), but represent an indicative classification.

Planet mass For radial velocity or microlensing planets, the key relevant observable is (projected) planet mass. Including a distinction between Earths and super-Earths at $2M_\oplus$ (cf. $1.9M_\oplus$ defined by Charbonneau et al. 2009, roughly equivalent to $2R_\oplus$; and $1M_\oplus$ by Valencia et al. 2007b), the classification proposed by Stevens & Gaudi (2013, see Figure 1.5) is:
- sub-Earths ($10^{-8}M_\oplus - 0.1M_\oplus$),
- Earths ($0.1M_\oplus - 2M_\oplus$),
- super-Earths ($2M_\oplus - 10M_\oplus$),
- Neptunes ($10M_\oplus - 100M_\oplus$),
- Jupiters ($100M_\oplus - 10^3M_\oplus$),
- super-Jupiters ($10^3M_\oplus - 13M_J$),
- brown dwarfs ($13M_J - 0.07M_\odot$), and
- stellar companions ($0.07M_\odot - 1M_\odot$).

Again, these are not universally-accepted 'definitions', and other boundaries have been adopted.

Statistics As of the end of 2017, the NASA Exoplanet Archive listed 3572 planets in nearly 600 multiple systems. Table 1.3 shows those that have mass or radius estimates. Some miscellaneous 'quantities of interest' are given in Table 1.5, and some 'extreme' transiting and radial velocity systems are listed in Table 1.6.

1.6.2 Giant planets

Despite widespread references to 'giant planets', a precise definition is not straightforward. In the context of

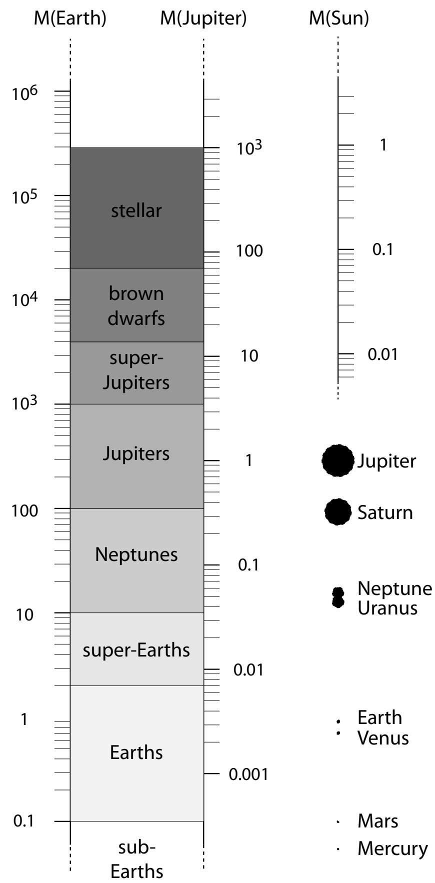

Figure 1.5: The classification of planet masses according to solar system objects, following the proposal by Stevens & Gaudi (2013). Masses of the solar system planets are shown at the right, with a circle size proportional to planet radius.

the steep mass function implied by microlensing surveys, Clanton & Gaudi (2014b) defined giant planets as having >50% H–He by mass, which, in the core accretion paradigm, would imply that their cores must have reached critical mass before gas disk dispersal.

They define a 'minimum' giant planet mass of $0.1M_J \sim 30\ M_\oplus$, since planets with $M_p \gtrsim 0.1M_J$ are likely composed of >50% H and He by mass, unless their protoplanetary disk was very massive (and thus the isolation mass was large) or the heavy element content was $\gg 10\%$. Counter examples might include HD 149026 b (Sato et al., 2005a; Carter et al., 2009), which is believed to have a highly metal-enriched composition, probably > 50% heavy elements by mass.

In comparison (cf. §12.2.2), Jupiter and Saturn ($\sim 0.3M_J$) primarily comprise H and He, while Neptune ($\sim 0.05M_J$) and Uranus ($\sim 0.05M_J$) contain roughly 5–15% H and He, 25% rock, and 60–70% ices, by mass, assuming the ice-to-rock ratio is protosolar (Podolak et al., 1991, 1995; Hubbard et al., 1995; Guillot, 2005).

Table 1.2: A selective (and subjective) chronology of exoplanet discoveries, including the first discoveries of some major instruments. Ordering is by received date of the published journal article. Theoretical contributions are (generally) not included.

Date	Subject	Reference
1987-12-14	Possible 1.7M_J radial velocity planet (later confirmed): γ Cep	Campbell et al. (1988)
1989-01-18	Possible 11M_J radial velocity planet (later confirmed): HD 114762	Latham et al. (1989)
1991-11-21	Multiple planet system from radio timing of millisec pulsar: PSR B1257+12	Wolszczan & Frail (1992)
1992-12-10	Possible 2.9M_J radial velocity planet (later confirmed): HD 62509	Hatzes & Cochran (1993)
1995-08-29	Radial velocity planet #1 (OHP–ELODIE: 0.47M_J, P = 4.2 d): 51 Peg	Mayor & Queloz (1995)
1996-01-22	Radial velocity planet #2 (Lick: 6.6M_J, P = 117 d): 70 Vir	Marcy & Butler (1996)
1996-02-15	Radial velocity planet #3 (Lick: 2.4M_J, P = 2.98 yr): 47 UMa	Butler & Marcy (1996)
1999-11-12	Photometric transit of a known planet (0.8-m APT): HD 209458	Henry et al. (1999)
1999-11-19	" (0.1-m STARE): HD 209458	Charbonneau et al. (2000)
1999-11-15	First (six) planets detected with Keck–HIRES	Vogt et al. (2000)
2000-01-03	Measurement of Rossiter–McLaughlin effect (ELODIE): HD 209458	Queloz et al. (2000a)
2000-12-27	System in (2:1) mean motion resonance (Lick/Keck): GJ 876 b and c	Marcy et al. (2001a)
2002-05-03	'Free-floating' cluster object of planet mass (sub-brown dwarf): S Ori 70	Zapatero Osorio et al. (2002)
2002-11-27	First planet discovered by transit photometry surveys (OGLE): OGLE–TR–56	Konacki et al. (2003a)
2002-12-11	Dust disk around white dwarf attributed to disrupted asteroid: G29–38	Jura (2003)
2003-12-23	Atmospheric (escaping) H I, O I, C II detected (HST–STIS): HD 209458 b	Vidal-Madjar et al. (2004)
2004-02-12	Microlensing planet #1 (confirmed, 2.6M_J): OGLE–2003–BLG–235L b	Bond et al. (2004)
2004-03-04	First planet detected with HARPS (radial velocity): HD 330075 b	Pepe et al. (2004a)
2004-08-06	First planet discovered by bright star transit photometry surveys: TrES–1 b	Alonso et al. (2004)
2004-10-06	Imaging of borderline planet/brown dwarf companion (VLT–NACO): GQ Lup	Neuhäuser et al. (2005)
2004-11-19	Probable planet detected by imaging (later confirmed): Fomalhaut	Kalas et al. (2005)
2005-02-03	Thermal emission (secondary eclipse) detected by Spitzer: TrES–1 b	Charbonneau et al. (2005)
2005-02-03	" " HD 209458 b	Deming et al. (2005b)
2005-04-05	Imaging of planet (4M_J) around brown dwarf (VLT–NACO): 2M J1207 b	Chauvin et al. (2005a)
2005-05-20	Microlensing planet #2 (3.8M_J): OGLE–2005–BLG–71	Udalski et al. (2005)
2005-05-24	Low-mass planet < 10$M_\oplus$ (6 – 8$M_\oplus$): GJ 876 d	Rivera et al. (2005)
2005-09-28	Low-mass microlensing planet (5.5$M_\oplus$): OGLE–2005–BLG–390L b	Beaulieu et al. (2006)
2006-02-13	Astrometric confirmation of radial velocity detection (HST–FGS): ϵ Eri b	Benedict et al. (2006)
2006-03-10	System with three 5 – 20$M_\oplus$ planets (HARPS): HD 69830	Lovis et al. (2006)
2006-08-12	First transiting planet from HATNet: HAT–P–1 b	Bakos et al. (2007b)
2006-08-15	Detection of day/night variation in thermal emission (Spitzer): υ And b	Harrington et al. (2006)
2006-09-22	First transiting planets from SuperWASP: WASP–1 b and WASP–2 b	Collier Cameron et al. (2007a)
2006-10-05	Planet in an open cluster (Hyades giant, Okayama): ϵ Tau b	Sato et al. (2007)
2006-10-24	Zeeman–Doppler imaging of a host star magnetic field: τ Boo	Catala et al. (2007)
2006-12-06	First determination of transiting planet absolute obliquity, ψ: HD 189733 b	Winn et al. (2007c)
2006-12-20	Planet around a K giant (Tautenburg): 4 UMa	Döllinger et al. (2007)
2007-01-19	Infrared spectrum (Spitzer–IRS): HD 189733 b	Grillmair et al. (2007)
2007-02-08	Atmospheric superrotation inferred from Spitzer: HD 189733 b	Knutson et al. (2007a)
2007-04-04	Super-Earth planet (7.7$M_\oplus$) in the habitable zone (HARPS): GJ 581 c	Udry et al. (2007)
2007-04-06	Planet detected in timing of p-mode pulsator: V391 Peg b	Silvotti et al. (2007)
2007-04-08	Atmospheric H_2O detected (Spitzer–IRAC): HD 189733 b	Tinetti et al. (2007b)
2007-05-08	System with five planets (from 18-yr radial velocity): 55 Cnc	Fischer et al. (2008)
2007-10-04	Long-period transiting planet (21.2 d): HD 17156 b	Barbieri et al. (2007)
2007-10-17	Planet candidate detected in timing of white dwarf: GD 66 b	Mullally et al. (2008)
2007-10-19	Microlensing 2-planet system with orbital motion: OGLE–2006–BLG–109L b/c	Gaudi et al. (2008)
2007-10-22	Detection of polarised light variations during transit: HD 189733 b	Berdyugina et al. (2008)
2008-01-04	First planet detected by CoRoT (space photometry): CoRoT–1 b	Barge et al. (2008)
2008-08-07	Planet detected in timing of eclipsing binary (previously suspected): HW Vir	Lee et al. (2009)
2008-09-07	Atmospheric CO_2, CO, H_2O detected (HST–NICMOS): HD 189733 b	Swain et al. (2009c)
2008-09-30	Planet detected by imaging (HST–ACS): Fomalhaut	Kalas et al. (2008)
2008-09-30	Three planets detected by imaging (Keck/Gemini): HR 8799	Marois et al. (2008b)
2008-11-10	Probable planet detected by imaging, later confirmed (VLT–NACO): β Pic	Lagrange et al. (2009b)
2009-01-28	Secondary eclipse detection by CoRoT: CoRoT–7 b	Snellen et al. (2009a)
2009-02-23	Transiting super-Earth (3 – 10$M_\oplus$) in 2-planet system: CoRoT–7 b	Léger et al. (2009)
2009-03-04	Short-period planet with evidence for tidal decay: WASP–18	Hellier et al. (2009a)
2009-03-24	Low-mass planet < 2$M_\oplus$ (1.9$M_\oplus$, HARPS): GJ 581 e	Mayor et al. (2009a)
2009-07-20	First transiting planet system known to be multiple: HAT–P–13 b/c	Bakos et al. (2009b)
2009-08-12	Possible retrograde orbit (later confirmed): HAT–P–7 b	Winn et al. (2009d)
2009-10-14	Relative orbit inclinations from astrometry (HST–FGS): υ And c/d	McArthur et al. (2010)
2009-10-20	Super-Earth planet (6.5$M_\oplus$) transiting an M star (MEarth): GJ 1214 b	Charbonneau et al. (2009)