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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 the dynamical perturbation of the star by the orbiting planet, delivered the first tangible results in the early 1990s. Radio pulsar timing achieved the first convincing detection of planetary mass bodies beyond the solar system in 1992. High-accuracy radial velocity (Doppler) measurements yielded the first suggestions of planetary-mass objects surrounding main sequence stars in 1988, with the first essentially unambiguous detection reported in 1995.

Progress since 1995 This discovery precipitated a changing mindset. Amongst the astronomical community at large, 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 was reported in 2003, the first of the wide-field bright star survey discoveries was reported in 2004, and the first discovery from space observations in 2008. A more complete observational chronology, of necessity both selective and subjective, is given in Table 1.1.

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

1.2 Discovery status

As of the cut-off date for this review, 2010 November 1, almost 500 exoplanets were known, with more than 50 multiple systems. Some statistics, according to discovery method, are listed 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. Around one third have very elliptical orbits, with $e \gtrsim 0.3$, compared with the largest eccentricities in the solar system, of about 0.2 for Mercury and Pluto (and just 0.05 for Jupiter). More than half are around the mass of Jupiter ($0.3-3M_{\rm J}$), and many 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 cannot have formed *in situ*. Others are located far out, at distances of 100 AU or more from their host star. Planets with orbits highly inclined to the star's equatorial plane occur frequently, some even with retrograde orbits.

Table 1.1: A selective chronology of exoplanet discoveries. Theoretical contributions are not included, and many other equally important discoveries could have been added. The specified date is the 'received date' of the published journal article. Discoveries are not listed if subsequently contested, and possible discoveries may be listed if subsequently confirmed. The first discoveries of some of the major survey instruments are also included.

Date	Subject	Reference
14-Dec-1987	Possible 1.7M_J radial velocity planet (later confirmed): γ Cep	Campbell et al. (1988)
18-Jan-1989	Possible 11M_J radial velocity planet (later confirmed): HD 114762	Latham et al. (1989)
21-Nov-1991	Multiple planet system from radio timing of millisec pulsar: PSR B1257+12	Wolszczan & Frail (1992)
10-Dec-1992	Possible 2.9M_J radial velocity planet (later confirmed): HD 62509	Hatzes & Cochran (1993)
29-Aug-1995	Radial velocity planet #1 (OHP–ELODIE: 0.47M_J, P = 4.2 d): 51 Peg	Mayor & Queloz (1995)
22-Jan-1996	Radial velocity planet #2 (Lick: 6.6M_J, P = 117 d): 70 Vir	Marcy & Butler (1996)
12-Nov-1999	Photometric transit of a known planet (0.8-m APT): HD 209458	Henry et al. (1999)
19-Nov-1999	" (0.1-m STARE): HD 209458	Charbonneau et al. (2000)
15-Nov-1999	First (six) planets detected with Keck–HIRES	Vogt et al. (2000)
3-Jan-2000	Measurement of Rossiter–McLaughlin effect (ELODIE): HD 209458	Queloz et al. (2000a)
27-Dec-2000	System in (2:1) mean motion resonance (Lick/Keck): GJ 876 b and c	Marcy et al. (2001a)
3-May-2002	'Free-floating' cluster object of planet mass (sub-brown dwarf): S Ori 70	Zapatero Osorio et al. (2002)
27-Nov-2002	First planet discovered by transit photometry surveys (OGLE): OGLE–TR–56	Konacki et al. (2003a)
23-Dec-2003	Atmospheric (escaping) H I, O I, C II detected (HST–STIS): HD 209458 b	Vidal-Madjar et al. (2004)
12-Feb-2004	Microlensing planet #1 (confirmed, 2.6M_J): OGLE–2003–BLG–235L b	Bond et al. (2004)
4-Mar-2004	First planet detected with HARPS (radial velocity): HD 330075 b	Pepe et al. (2004)
6-Aug-2004	First planet discovered by bright star transit photometry surveys: TrES–1	Alonso et al. (2004)
6-Oct-2004	Imaging of borderline planet/brown dwarf companion (VLT–NACO): GQ Lup	Neuhäuser et al. (2005)
19-Nov-2004	Probable planet detected by imaging (later confirmed): Fomalhaut	Kalas et al. (2005)
3-Feb-2005	Thermal emission (secondary eclipse) detected by Spitzer: TrES–1 b	Charbonneau et al. (2005)
3-Feb-2005	" HD 209458 b	Deming et al. (2005b)
5-Apr-2005	Imaging of planet (4M_J) around brown dwarf (VLT–NACO): 2M J1207 b	Chauvin et al. (2005a)
20-May-2005	Microlensing planet #2 (3.8M_J): OGLE–2005–BLG–071	Udalski et al. (2005)
24-May-2005	Low-mass planet < 10$M_\oplus$ (6 – 8$M_\oplus$): GJ 876 d	Rivera et al. (2005)
28-Sep-2005	Low-mass microlensing planet (5.5$M_\oplus$): OGLE–2005–BLG–390L b	Beaulieu et al. (2006)
13-Feb-2006	Astrometric confirmation of radial velocity detection (HST–FGS): ϵ Eri b	Benedict et al. (2006)
10-Mar-2006	System with three Neptune-mass planets (5 – 20$M_\oplus$, HARPS): HD 69830	Lovis et al. (2006)
12-Aug-2006	First transiting planet from HATNet: HAT–P–1 b	Bakos et al. (2007b)
15-Aug-2006	Detection of day/night variation in thermal emission (Spitzer): υ And b	Harrington et al. (2006)
22-Sep-2006	First transiting planets from SuperWASP: WASP–1 b and WASP–2 b	Collier Cameron et al. (2007a)
5-Oct-2006	Planet in an open cluster (Hyades giant, Okayama): ϵ Tau b	Sato et al. (2007)
20-Dec-2006	Planet around a K giant (Tautenburg): 4 UMa	Döllinger et al. (2007)
19-Jan-2007	Infrared spectrum (Spitzer–IRS): HD 189733 b	Grillmair et al. (2007)
4-Apr-2007	Super-Earth planet (7.7$M_\oplus$) in the habitable zone (HARPS): GJ 581 c	Udry et al. (2007)
6-Apr-2007	Planet detected in timing of p-mode pulsator: V391 Peg b	Silvotti et al. (2007)
8-Apr-2007	Atmospheric H_2O detected (Spitzer–IRAC): HD 189733 b	Tinetti et al. (2007b)
8-May-2007	System with five planets (from 18-yr radial velocity): 55 Cnc	Fischer et al. (2008)
4-Oct-2007	Long-period transiting planet (21.2 d): HD 17156 b	Barbieri et al. (2007)
17-Oct-2007	Planet candidate detected in timing of white dwarf: GD 66 b	Mullally et al. (2008)
19-Oct-2007	Microlensing planets with orbital rotation: OGLE–2006–BLG–109L b,c	Gaudi et al. (2008)
4-Jan-2008	First planet detected by CoRoT (space photometry): CoRoT–1 b	Barge et al. (2008)
7-Aug-2008	Planet detected in timing of eclipsing binary (previously suspected): HW Vir	Lee et al. (2009)
7-Sep-2008	Atmospheric CO_2, CO, H_2O detected (HST–NICMOS): HD 189733 b	Swain et al. (2009c)
30-Sep-2008	Planet detected by imaging (HST–ACS): Fomalhaut	Kalas et al. (2008)
30-Sep-2008	Three planets detected by imaging (Keck/Gemini): HR 8799	Marois et al. (2008b)
10-Nov-2008	Probable planet detected by imaging, later confirmed (VLT–NACO): β Pic	Lagrange et al. (2009b)
28-Jan-2009	Secondary eclipse detection by CoRoT: CoRoT–7 b	Snellen et al. (2009a)
23-Feb-2009	Transiting super-Earth (3 – 10$M_\oplus$): CoRoT–7 b	Léger et al. (2009)
24-Mar-2009	Low-mass planet < 2$M_\oplus$ (1.9$M_\oplus$, HARPS): GJ 581 e	Mayor et al. (2009a)
20-Jul-2009	Multiple system with one transiting planet: HAT–P–13 b,c	Bakos et al. (2009b)
12-Aug-2009	Possible retrograde orbit (later confirmed): HAT–P–7 b	Winn et al. (2009)
14-Oct-2009	Relative orbit inclinations from astrometry (HST–FGS): υ And c, d	McArthur et al. (2010)
20-Oct-2009	Super-Earth planet (6.5$M_\oplus$) transiting an M star (MEarth): GJ 1214 b	Charbonneau et al. (2009)
2-Nov-2009	Spectrum of an imaged planet (VLT–NACO): HR 8799 c	Janson et al. (2010)
16-Nov-2009	First transiting planet from Kepler (space photometry): Kepler–4 b	Borucki et al. (2010b)
17-Feb-2010	Triple (Laplace) resonance (Keck–HIRES): GJ 876 b, c, e	Rivera et al. (2010)
28-Jul-2010	System with two transiting planets, with timing variations: Kepler–9 b, c	Holman et al. (2010)
12-Aug-2010	System with (possibly) seven planets (HARPS): HD 10180	Lovis et al. (2011)

Table 1.2: Exoplanet detection statistics, from `exoplanet.eu`*, 2010 November 1. Notes: (1) 358 of these planets are radial velocity discoveries (see Chapter 2 and Appendix C), others are measurements of transiting systems; a few have also been measured by astrometry, although none have been discovered by astrometry; (2) most are transit discoveries, although a few were discovered by radial velocity measurements (see Chapter 6 and Appendix D); some are known to be in multiple systems from subsequent radial velocity measurements; (3) see Chapter 5; (4) see Chapter 7; (5) see Chapter 4; (6) objects of sub-brown dwarf mass, existing in apparent isolation in young clusters (see Chapter 9); (7) is not the sum of the preceding, since some planets have been detected by more than one technique (principally, transit discoveries with radial velocity follow-up).*

Category	Systems	Multiple	Planets
Detections			
Radial velocity[1]	390	45	461
Transits[2]	105	7	106
Microlensing[3]	10	1	11
Imaging[4]	10	1	12
Timing[5]	6	3	10
Cluster objects[6]	6	–	6
Total number of planets[7]			494
Unconfirmed or retracted	94	3	97

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. The first exoplanet atmospheres have been probed through secondary eclipse photometry and spectroscopy.

Of the multiple exoplanet systems, massive planets orbiting in mean motion resonance are common, presenting a certain challenge to explain their ubiquity. The first triple-planet Laplace resonance has been discovered, as have prominent transit time variations in a two-planet transiting system. Systems with multiple lower-mass planets are being found in increasing numbers as the radial velocity surveys improve their detection threshold and increase their temporal baseline. The five-planet system 55 Cnc has been overtaken by the (possible) six-planet system GJ 581 with a $3.1M_\oplus$ planet in the habitable zone, and up to seven planets with five of Neptune-mass in the case of HD 10180.

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 2010. It is formulated as an overall introduction to exoplanet research for those new to the field, 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.

Radial velocity Chapter 2 covers the many aspects of radial velocity (Doppler) measurements, including the different instrumental approaches being used and under development. It includes a basic treatment of planetary orbits, indicating how radial velocity measurements (as well as astrometric measurements, independently and together) provide access to the planet's orbital parameters. As the most successful of the discovery techniques to date, at least in numerical terms, 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 double and multiple stars. For multiple planetary systems, this chapter also provides an introduction to the concepts of resonances, dynamical stability, and dynamical packing. 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. Since the largest astrometric displacements expected for the most massive nearby planets amount to of order 1 milliarcsec, comparable to the current state-of-the art in astrometric measurements from space, few planets can yet be confirmed through their astrometric displacements, and none have been discovered by astrometry alone. The limiting factors for ground-based and space-based instruments are summarised. The panorama of astrometric discovery and characterisation is expected to change substantially with the advent of microarcsec astrometry, both from the ground and more particularly from space.

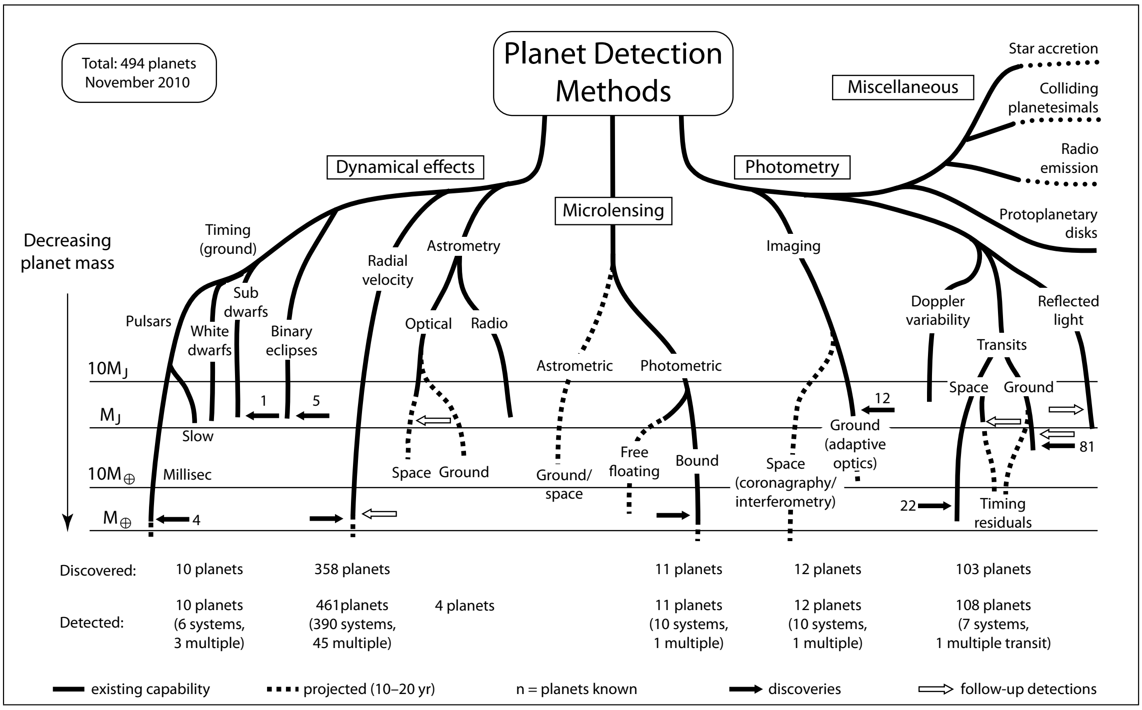

Figure 1.1: Detection methods for exoplanets. The lower limits of the lines indicate the detectable masses that are in principle within reach of present measurements (solid lines), and those that might be expected within the next 10–20 years (dashed). The (logarithmic) mass scale is shown at left. The miscellaneous signatures to the upper right are less well quantified in mass terms. Solid arrows indicate detections according to approximate mass. Open arrows indicate that relevant measurements of previously-detected systems have been made. The figure takes no account of the numbers of planets that may ultimately be detectable by each method. Adapted from Perryman (2000, Figure 1), with permission from the Institute of Physics Publishing Ltd.

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 using radio pulsar timing measurements in 1991. 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 recently 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. Alone amongst the techniques in sampling primarily very distant exoplanetary systems, its main disadvantage is that it can only provide a single measurement epoch spanning hours or days. A particularly noteworthy result was the measurement, reported in 2008, of a system of two planets 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 a measurement 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 are of relevance only for planets whose orbits happen to lie essentially orthogonal to the plane of the sky, this constrained geometry allows both the mass of the planet to be determined unambiguously (without the $\sin i$ indeterminacy inherent in radial velocity observations) and, of major importance for exoplanet characterisation, its radius. 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. Further insights into the atmospheres of the gas giants are being obtained from transit and secondary eclipse spectroscopy.

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 interferometry) are described, along with the results obtained to date. 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 metallicities, and the theories put forward to explain the observed correlation between the occurrence of exoplanets and host-star metallicity. It also reviews the asteroseismology investigations that have been carried out on a few exoplanet host stars, and the characteristics of their X-ray emission.

Brown dwarfs Chapter 9 provides an introduction to 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 10–12 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 giants, of masses $\gtrsim 10M_\oplus$, 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 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 the origin of water on Earth, orbital stability, planet obliquities, the origin of the Moon, planet migration, and the origin and evolution of the Earth's atmosphere. 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.

1.4 Astronomical terms and units

For those less familiar with astronomical terms and nomenclature, a brief summary of some relevant concepts is as follows.

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. Orbits are characterised by their period P, semi-major axis a, eccentricity e, 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.

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 ($M_\mathrm{J}, R_\mathrm{J}$) for the gas giants, or Earth units ($M_\oplus, R_\oplus$) for planets closer to terrestrial mass. Numerical values for these and other quantities are given in Appendix A.

It may be noted that the *de facto* definition of R_J in terms of Jupiter's equatorial radius at 10^5 Pa means that, due to its oblateness, Jupiter's own mean radius is actually $0.978 R_\mathrm{J}$.

Star distances and masses Stellar distances are given in parsec (pc). As the basic unit of astronomical distance based on the measurement of trigonometric parallax, this is the distance at which the mean Sun–Earth distance (the astronomical unit, or AU) subtends an angle of 1 arcsec (1 pc $\simeq 3.1 \times 10^{16}$ m $\simeq$ 3.26 light-years).

For reference, 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 about 50–100 pc.

In general, stellar masses range from around $0.1 - 30\,M_\odot$, with spectral types providing a conventional classification related to the primary stellar properties of temperature and luminosity. The Sun is of spectral type G2V: 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 Object names such as 70 Vir (for 70 Virginis) and β Pic (for β Pictoris) reflect constellation-based nomenclature, while other designations reflect discovery catalogues or techniques variously labeled with catalogue running numbers (e.g. HD 114762) or according to celestial 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 $\simeq$ 12 mag, but with a completeness between 7.3–9.0 mag depending on Galactic latitude and spectral type (Perryman et al., 1997), and detailed further in §8.1.1.

BD (Bonner Durchmusterung): the BD was the first of the three-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 in Argentina (the Córdoba Durchmusterung, or CD) by Thomme starting in 1892. The southern skies were surveyed from the Cape of Good Hope (the Cape Durchmusterung, or CPD) by Gill & Kapteyn around 1900. Stars tend to be assigned their DM (Durchmustering) number if they are not part of the HD or HIP catalogues.

Nearby stars: these are often designated according to their inclusion in the Catalogue of Nearby Stars (CNS), described further in §8.1.2. Such stars appear in the CDS SIMBAD data base as GJ nnn, although the alternatives Gliese nnn or Gl nnn are often used.

Exoplanet names 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).

The naming convention adopted for microlensing planets, where the host star is generally invisible, is described on page 98.

Other units In aiming for a consistent usage of terms and nomenclature, units referred to in the published literature, or in some of the figures, have occasionally been unified. Usage here follows, as far as is considered reasonable, the International System of Units (SI).

Astronomical measures of density generally use the non-SI unit of g cm^{-3}. Densities here are expressed in units of Mg m^{-3}, conforming to SI, and with the same numerical values (and 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 Pa $\equiv$ 1 N m^{-2}, and the bar (1 bar $\equiv 10^5$ 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 systematically 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.

Certain units central to astronomy, notably the astronomical units of mass and radius noted above, deviate from SI, but are retained in this treatment. While the astronomical unit is accepted within the SI, consistent with common astronomical usage it is indicated here as AU (although the CIPM designates the unit 'ua').

Table 1.3: Some on-line information and catalogues of particular relevance to exoplanet research.

URL	Content	Comment
Exoplanet catalogues:		
exoplanet.eu	Extrasolar Planets Encyclopedia	Reference catalogue and bibliography
exoplanets.org	Exoplanet Data Explorer	Orbit database (Jones et al., 2008a)
nsted.ipac.caltech.edu	Star and Exoplanet Database	Exoplanet database (Ali et al., 2007)
Transit data:		
www.inscience.ch/transits	Exoplanet Transit Parameters	Compilation of transiting exoplanets
var.astro.cz/ETD	Exoplanet Transit Database	Compilation of exoplanet transits
idoc-corot.ias.u-psud.fr/	CoRoT Mission	Public access
archive.stsci.edu/kepler/planet_candidates.html	Kepler Mission	Released planetary candidates
www.wasp.le.ac.uk/public/	SuperWASP Project	Public archive
Related catalogues:		
www.dwarfarchives.org	Compendium of M, L, T Dwarfs	Photometry, spectroscopy, astrometry
circumstellardisks.org	Catalogue of Circumstellar Disks	Pre-main sequence and debris disks
General resources:		
adsabs.harvard.edu/abstract_service.html	NASA Astrophysics Data System	Digital bibliographic data, with arXiv
simbad.u-strasbg.fr/simbad	CDS SIMBAD	Astronomical object data base

1.5 Definition of a planet

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 1c, is nevertheless recognised as being somewhat ambiguous due to the difficulties in formulating precise definitions of shape and orbital ‘clearing’.

IAU 2003 recommendation Exoplanet classification is facilitated by the fact that a distinction in mass between planets and smaller bodies is not yet relevant. In contrast, nomenclature is complicated by the problems of distinguishing planets from brown dwarfs.

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 $13M_J$ 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).

Adopted convention In this treatment, orbiting substellar objects are referred to as planets below $\sim 13M_J$, and as brown-dwarf planets above that threshold (if appropriate to the context), whatever their likely formation mechanism (see box on page 210).

Isolated objects are referred to as sub-brown dwarfs or brown dwarfs according to their estimated mass lying below or above the deuterium-burning threshold, and only as free-floating planets if evidence points to their having been formed as a planet and subsequently dynamically ejected from the original host system. No such objects have yet been confirmed.

Attempts to formulate a precise definition of a planet are confronted by a number of difficulties, summarised by Basri & Brown (2006). A definition dispensing with upper and lower mass limits is offered, and further quantified, by Soter (2006): *A planet is an end product of disk accretion around a primary star or substar.*

1.6 On-line reference compilations

In general, references to on-line compilations or resources have been avoided because of changing URLs, or the frequent absence of long-term maintenance. Many www sites, nevertheless, are repositories of up-to-date information, and a selection of some of the most relevant are listed in Table 1.3. Many other groups host their own information pages.