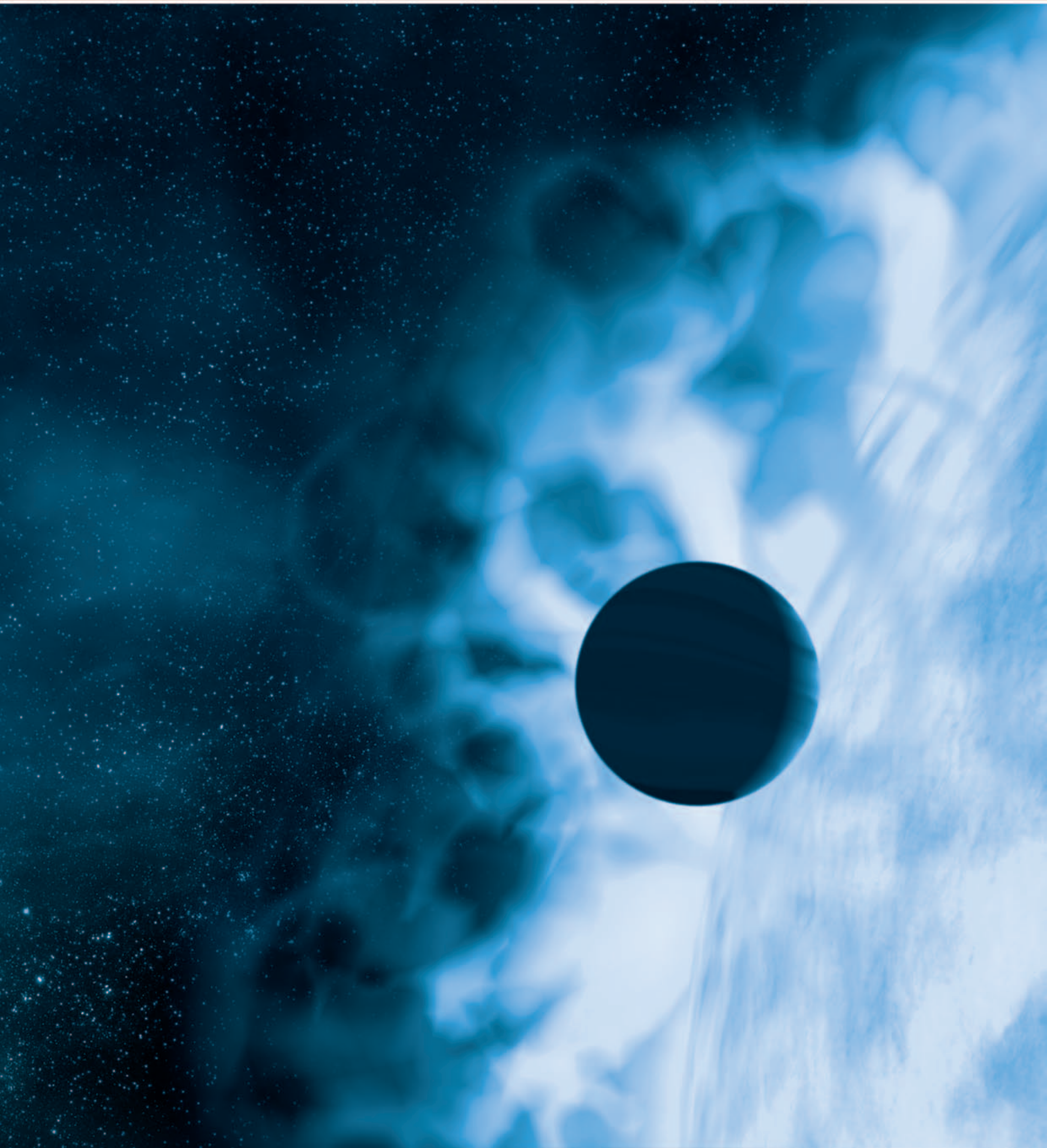
ESA-ESO Working Groups

Report No.1 Extra-Solar Planets

March 2005



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Report by the ESA–ESO Working Group on Extra-Solar Planets

4 March 2005

Summary

Various techniques are being used to search for extra-solar planetary signatures, including accurate measurement of radial velocity and positional (astrometric) displacements, gravitational microlensing, and photometric transits. Planned space experiments promise a considerable increase in the detections and statistical knowledge arising especially from transit and astrometric measurements over the years 2005–15, with some hundreds of terrestrial-type planets expected from transit measurements, and many thousands of Jupiter-mass planets expected from astrometric measurements.

Beyond 2015, very ambitious space (Darwin/TPF) and ground (OWL) experiments are targeting direct detection of nearby Earth-mass planets in the habitable zone and the measurement of their spectral characteristics. Beyond these, 'Life Finder' (aiming to produce confirmatory evidence of the presence of life) and 'Earth Imager' (some massive interferometric array providing resolved images of a distant Earth) appear as distant visions.

This report, to ESA and ESO, summarises the direction of exo-planet research that can be expected over the next 10 years or so, identifies the roles of the major facilities of the two organisations in the field, and concludes with some recommendations which may assist development of the field.

The report has been compiled by the Working Group members and experts (page iii) over the period June–December 2004.

Introduction & Background

Following an agreement to cooperate on science planning issues, the executives of the European Southern Observatory (ESO) and the European Space Agency (ESA) Science Programme and representatives of their science advisory structures have met to share information and to identify potential synergies within their future projects. The agreement arose from their joint founding membership of EIROforum (http://www.eiroforum.org) and a recognition that, as pan-European organisations, they served essentially the same scientific community.

At a meeting at ESO in Garching during September 2003, it was agreed to establish a number of working groups that would be tasked to explore these synergies in important areas of mutual interest and to make recommendations to both organisations. The chair and co-chair of each group were to be chosen by the executives but thereafter, the groups would be free to select their membership and to act independently of the sponsoring organisations. The first working group to be established was on the topic of Extra-Solar Planet research, both detection and physical study, over a period extending from now until around 2015. The group worked on its report from June until December 2004 and reported its conclusions and recommendations to a second ESA-ESO meeting, held at ESA HQ in Paris in February 2005.

Terms of Reference and Composition

The goals set for the working group were to provide:

- A survey of the field: this will comprise: (a) a review of the methods used or envisaged for extra-solar planet detection and study; (b) a survey of the associated instrumentation world-wide (operational, planned, or proposed, on-ground and in space); (c) for each, a summary of the potential targets, accuracy and sensitivity limits, and scientific capabilities and limitations.

- An examination of the role of ESO and ESA facilities: this will: (a) identify areas in which current and planned ESA and ESO facilities will contribute; (b) analyse the expected scientific returns and risks of each; (c) identify areas of potential scientific overlap, and thus assess the extent to which the facilities complement or compete; (d) identify open areas which merit attention by one or both organisations (for example, follow-up observations by ESO to maximise the return from other major facilities); (e) conclude on the scientific case for the very large facilities planned or proposed.

The working group membership was established by the chair and co-chair: the report is not a result of consultation with the community as a whole. The experts contributed considerable information for the report, but the conclusions and recommendations are the responsibility of the members.

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1 Survey of the Field

1.1 Introduction

The field of exo-planet research has exploded dramatically since the discovery of the first such systems in 1995. Underlying this huge interest three main themes of exo-planet research can be identified: (a) characterising and understanding the planetary populations in our Galaxy; (b) understanding the formation and evolution of planetary systems (e.g., accretion, migration, interaction, mass-radius relation, albedo, distribution, host star properties, etc.); (c) the search for and study of biological markers in exo-planets, with resolved imaging and the search for intelligent life as 'ultimate' and much more distant goals.

Detection methods for extra-solar planets can be broadly classified into those based on: (i) dynamical effects (radial velocity, astrometry, or timing in the case of the pulsar planets); (ii) microlensing (astrometric or photometric); (iii) photometric signals (transits and reflected light); (iv) direct imaging from ground or space in the optical or infrared; and (v) miscellaneous effects (such as magnetic superflares, or radio emission). Each have their strengths, and advances in each field will bring specific and often complementary discovery and diagnostic capabilities. Detections are a pre-requisite for the subsequent steps of detailed physical-chemical characterisation demanded by the emerging discipline of exo-planetology.

As of December 2004, 135 extra-solar planets have been discovered from their radial velocity signature, comprising 119 systems of which 12 are double and 2 are triple. One of these planets has also been observed to transit the parent star. Four additional confirmed planets have been discovered through transit detections using data from OGLE (and confirmed through radial velocity measurements), and one, TrES-1, using a small 10-cm ground-based telescope. One further, seemingly reliable, planet candidate has been detected through its microlensing signature. The planets detected to date (apart from those surrounding radio pulsars, which are not considered further in this report) are primarily 'massive' planets, of order $1\,M_{\rm J}$, but extending down to perhaps $0.05\,M_{\rm J}$ (around $15\,M_\oplus$) for three short-period systems, although the inclination (and hence true mass) of two of these is unknown[1].

Detection methods considered to date are summarised in Figure 1, which also gives an indication of the lower mass limits which are likely to be reached in the foreseeable future for each method. More information and ongoing projects are given in Jean Schneider's www page: http://www.obspm.fr/encycl/searches.html.

An earlier ESO Working Group on the 'Detection of Extra-Solar Planets' submitted a report with detailed recommendations in 1997 (Paresce et al., 1997). A summary and status of these recommendations is attached as Appendix C.

[1] the following notation is used: $M_{\rm J}$ = Jupiter mass; $M_\oplus$ = Earth mass $\sim 0.003\,M_{\rm J}$.

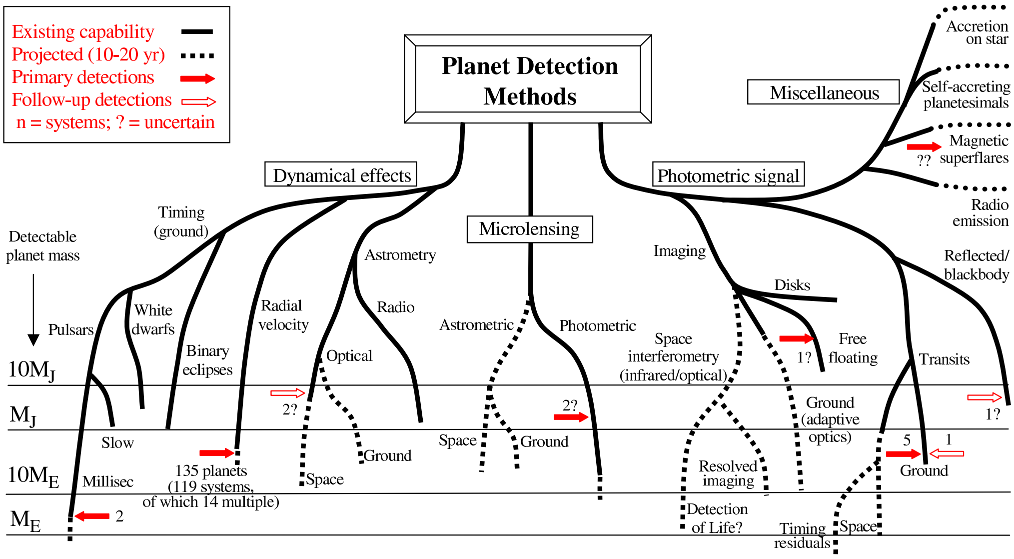


Figure 1: Detection methods for extra-solar planets, updated from Perryman (2000). The lower extent of the lines indicates, roughly, the detectable masses that are in principle within reach of present measurements (solid lines), and those that might be expected within the next 10–20 years (dashed). The (logarithmic) mass scale is shown at left. The miscellaneous signatures to the upper right are less well quantified in mass terms. Solid arrows indicate (original) detections according to approximate mass, while open arrows indicate further measurements of previously-detected systems. '?' indicates uncertain or unconfirmed detections. The figure takes no account of the numbers of planets that may be detectable by each method.

1.2 The Search for Earth-Mass Planets and Habitability

The search for planets around stars in general, and Earth-mass planets in particular, is motivated by efforts to understand their frequency of occurrence (as a function of mass, semi-major axis, eccentricity, etc.) and their formation mechanism and, by analogy, to gain an improved understanding of the formation of our own Solar System. Search accuracies will progressively improve to the point that the detection of telluric planets in the 'habitable zone' will become feasible, and there is presently no reason to assume that such planets will not exist in large numbers. Improvements in spectroscopic abundance determinations, whether from Earth or space, and developments of atmospheric modelling, will lead to searches for planets which are progressively habitable, inhabited by micro-organisms, and ultimately by intelligent life (these may or may not prove fruitful). Search strategies will be assisted by improved understanding of the conditions required for development of life on Earth.

Very broadly, the search for potentially habitable planets is being concentrated around Sun-like stars (spectral type and age), focussing on Earth-mass planets, in low-eccentricity orbits at about 1 AU representing the 'continuously habitable zone' (the habitable zone is the distance range from the parent star over which liquid water is likely to be present; the continuously habitable zone is the region throughout which liquid water should have been present over a significant fraction of the star's main-sequence lifetime). Further details and potential spectral diagnostics of life are given in this section. Such considerations may imply that the fraction of habitable planets is small, but they should add to the knowledge of where to look.

Assessment of the suitability of a planet for supporting life, or habitability, is based on our knowledge of life on Earth. With the general consensus among biologists that carbon-based life requires water for its self-sustaining chemical reactions, the search for habitable planets has therefore focused on identifying environments in which liquid water is stable over billions of years. Earth's habitability over early geological time scales is complex, but its atmosphere is thought to have experienced an evolution in the greenhouse blanket of CO_2 and H_2O to accommodate the 30% increase in the Sun's luminosity over the last 4.6 billion years in order to sustain the presence of liquid water evident from geological records. In the future, the Sun will increase to roughly three times its present luminosity by the time it leaves the main sequence, in about 5 Gyr.

The habitable zone is consequently presently defined by the range of distances from a star where liquid water can exist on the planet's surface. This is primarily controlled by the star-planet separation, but is affected by factors such as planet rotation combined with atmospheric convection. For Earth-like planets orbiting main-sequence stars, the inner edge is bounded by water loss and the runaway greenhouse effect, as exemplified by the CO_2-rich atmosphere and resulting temperature of Venus. The outer boundary is determined by CO_2 condensation and runaway glaciation, but it may be extended outwards by factors such as internal heat sources including long-lived radionuclides (U^{235}, U^{238}, K^{40} etc., as on Earth), tidal heating due to gravitational interactions (as in the case of Jupiter's moon Io), and pressure-induced far-infrared opacity of H_2, since even for effective temperatures as low as 30 K, atmospheric basal temperatures can exceed the melting point of water. These considerations result, for a $1\,M_\odot$ star, in an inner habitability boundary at about 0.7 AU and an outer boundary at around 1.5 AU or beyond. The habitable zone evolves outwards with time because of the increasing luminosity of the Sun with age, resulting in a narrower width of the continuously habitable zone over ~ 4 Gyr of around 0.95–1.15 AU. Positive feedback due to the greenhouse effect and planetary albedo variations, and negative feedback due to the link between atmospheric CO_2 level and surface temperature may limit these boundaries further. Migration of the habitable zone to much larger distances, 5–50 AU, during the short period of post-main-sequence evolution corresponding to the sub-giant and red giant phases, has been considered.

Within the ~ 1 AU habitability zone, Earth 'class' planets can be considered as those with masses between about 0.5–10 $M_\oplus$ or, equivalently assuming Earth density, radii between 0.8–2.2 $R_\oplus$. Planets below this mass in the habitable zone are likely to lose their life-supporting atmospheres because of their low gravity and lack of plate tectonics, while more massive systems are unlikely to be habitable because they can attract a H-He atmosphere and become gas giants. Habitability is also likely to be governed by the range of stellar types for which life has enough time to evolve, i.e. stars not more massive than spectral type A. However, even F stars have narrower continuously habitable zones because they evolve more strongly (and rapidly), while planets orbiting in the habitable zones of late K and M stars become trapped in synchronous rotation due to tidal damping, which may preclude life apart from close to the light-shadow line. Mid- to early-K and G stars may therefore be optimal for the development of life.

Owen (1980) argued that large-scale biological activity on a telluric planet necessarily produces a large quantity of O_2. Photosynthesis builds organic molecules from CO_2 and H_2O, with the help of H^+ ions which can be provided from different sources. In the case of oxygenic bacteria on Earth, H^+ ions are provided by the photodissociation of H_2O, in which case oxygen is produced as a by-product. However, this is not the case for anoxygenic bacteria, and thus O_2 is to be considered as a possible but not a necessary by-product of life (for this signature of biological activity, as well as for any other, a key issue is that of false positives, i.e. cases where the signature is detected but there is no actual life on the planet, while the case of false negatives, when there is some life on the planet but the signature is absent, is significantly less 'serious'). Indeed, Earth's atmosphere was O_2-free until about 2 billion years ago, suppressed for more than 1.5 billion years after life originated. Owen (1980) noted the possibility, quantified by Schneider (1994) based on transit measurements, of using the 760-nm band of oxygen as a spectroscopic tracer of life on another planet since, being highly reactive with reducing rocks and volcanic gases, it would disappear in a short time in the absence of a continuous production mechanism. Plate tectonics and volcanic activity provide a sink for free O_2, and are the result of internal planet heating by radioactive uranium and of silicate fluidity, both of which are expected to be generic whenever the mass of the planet is sufficient and when liquid water is present. For small enough planet masses, volcanic activity disappears some time after planet formation, as do the associated oxygen sinks.

O_3 is itself a tracer of O_2 and, with a prominent spectral signature at 9.6 μm in the infrared where the planet/star contrast is significantly stronger than in the optical (1.4×10^{-7} rather than 2×10^{-10} for the Earth/Sun case), should be easier to detect than the visible wavelength lines. These considerations are motivating the development of infrared space interferometers for the study of bands such as H_2O at 6–8 μm, CH_4 at 7.7 μm, O_3 at 9.6 μm, CO_2 at 15 μm and H_2O at 18 μm. Higher resolution studies might reveal the presence of CH_4, its presence on Earth resulting from a balance between anaerobic decomposition of organic matter and its interaction with atmospheric oxygen; its highly disequilibrium co-existence with O_2 could be strong evidence for the existence of life.

The possibility that O_2 and O_3 are not unambiguous identifications of Earth-like biology, but rather a result of abiotic processes, has been considered in detail by Léger et al. (1999) and Selsis et al. (2002). They considered various production processes such as abiotic photodissociation of CO_2 and H_2O followed by the preferential escape of hydrogen from the atmosphere. In addition, cometary bombardment could bring O_2 and O_3 sputtered from H_2O by energetic particles, depending on the temperature, greenhouse blanketing, and presence of volcanic activity. They concluded that a simultaneous detection of significant amounts of H_2O and O_3 in the atmosphere of a planet in the habitable zone presently stands as a criterion for large-scale photosynthetic activity on the planet. Such an activity on a planet illuminated by a star similar to the Sun, or cooler, is likely to be a significant indication that there is local biological activity, because this synthesis requires the storage of the energy of at least 2 photons (8 in the case on Earth) prior to the synthesis of organic molecules from H_2O and CO_2. This is likely to require delicate systems that have developed during a biological evolutionary process. The biosignature based on O_3 seems to be robust because no counter example has been demonstrated. It is not the case for the biosignature based on O_2 (Selsis et al., 2002), where false positives can be encountered. This puts a hierarchy between observations that can detect O_2 and those that can detect O_3.

Habitability may be further confined within a narrow range of [Fe/H] of the parent star (Gonzalez, 1999b). If the occurrence of gas giants decreases at lower metallicities, their shielding of inner planets in the habitable zone from frequent cometary impacts, as occurs in our Solar System, would also be diminished. At higher metallicity, asteroid and cometary debris left over from planetary formation may be more plentiful, enhancing impact probabilities. Gonzalez (1999a) has also investigated whether the anomalously small motion of the Sun with respect to the local standard of rest, both in terms of its pseudo-elliptical component within the Galactic plane, and its vertical excursion with respect to the mid-plane, may be explicable in anthropic terms. Such an orbit could provide effective shielding from high-energy ionising photons and cosmic rays from nearby supernovae, from the X-ray background by neutral hydrogen in the Galactic plane, and from temporary increases in the perturbed Oort comet impact rate.

1.3 Present Limits: Ground and Space

Figure 2 illustrates the detection domains for the radial velocity, astrometry, and transit methods as a function of achievable accuracy. It also shows the location of the exo-planets known to date, in a mass-orbital radius (period) diagram.

The fundamental accuracy limits of each method are not yet firmly established, although such knowledge is necessary to predict the real performances of dedicated surveys on ground and in space. Granular flows and star spots on the surface of late-type stars place specific limits on the photometric stability, the stability

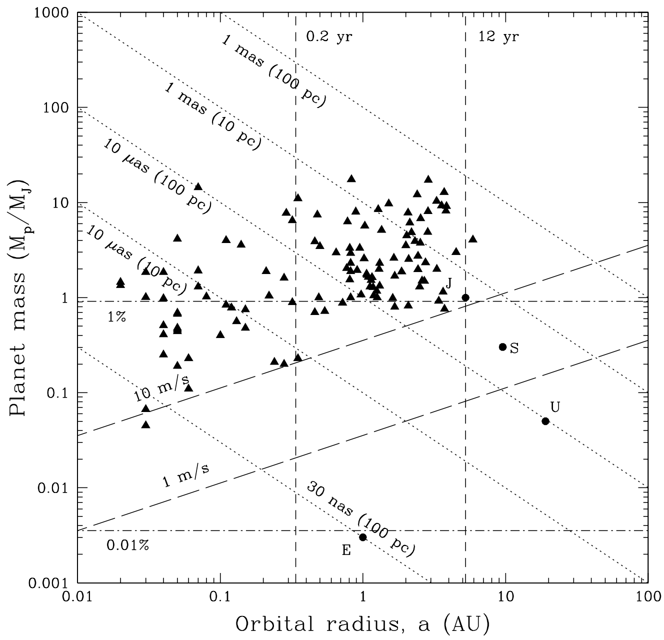


Figure 2: Detection domains for methods exploiting planet orbital motion, as a function of planet mass and orbital radius, assuming $M_* = M_\odot$. Lines from top left to bottom right show the locus of astrometric signatures of 1 milli-arcsec and 10 micro-arcsec at distances of 10 and 100 pc; a measurement accuracy 3–4 times better would be needed to detect a given signature. Vertical lines show limits corresponding to orbital periods of 0.2 and 12 years, relevant for Gaia (where very short and very long periods cannot be detected) although not for SIM. Lines from top right to bottom left show radial velocities corresponding to $K = 10$ and $K = 1$ m s^{-1}; a measurement accuracy 3–4 times better would be needed to detect a given value of K. Horizontal lines indicate photometric detection thresholds for planetary transits, of 1% and 0.01%, corresponding roughly to Jupiter and Earth radius planets respectively (neglecting the effects of orbital inclination, which will diminish the probability of observing a transit as a increases). The positions of Earth (E), Jupiter (J), Saturn (S) and Uranus (U) are shown, as are the lower limits on the masses of known planetary systems as of December 2004 (triangles).

of the photocentric position, and the stability of spectroscopically-derived radial velocities, whether these observations are made from ground or space. A series of hydrodynamical convection models covering stellar objects from white dwarfs to red giants has been used to give estimates of the photometric and photocentric stellar variability in wavelength-integrated light across the HR diagram (Svensson & Ludwig, 2005).

(a) Radial velocity experiment accuracies are close to the values of around 1–3 m s^{-1} at which atmospheric circulation and oscillations limit measurement precision, implying mass detection limits only down to 0.01–0.1 $M_{\rm J}$ (depending on orbital period); detection of an Earth in the habitable zone would require accuracies of $\sim 0.03 - 0.1$ m s^{-1}. Observations from space will not improve these limits, and no high-precision radial velocity measurements from space have been proposed.

The idea of 'stacking up' many radial velocity observations to average the effects of stellar oscillations is appealing, but faces several complications: (i) even if p-mode oscillation effects can be minimised, beating amongst these modes may induce large radial-velocity variations (up to $10\,\mathrm{m\,s^{-1}}$ peak-to-peak) over timescales of a few hours, specifically some 5–6 hours for μ Arae (Bouchy, private communication). The star will therefore need to be observed over several hours for each epoch (radial velocity point); (ii) simulations by Bouchy (private communication) show that a precision of $\sim 1\,\mathrm{m\,s^{-1}}$ is reached in about 15–20 min, while the gain is much less rapid with increasing observation time. A precision of $0.1\,\mathrm{m\,s^{-1}}$ (still insufficient for the detection of the Earth around the Sun) will therefore be very expensive in terms of telescope time; (iii) a wavelength calibration precision from night-to-night is then needed at the level of the long-term precision targeted. Reference calibration to $0.1\,\mathrm{m\,s^{-1}}$ will require further improvements in calibration techniques. With HARPS, a precision of about $0.5\,\mathrm{m\,s^{-1}}$ is reached, as illustrated by asteroseismology results on μ Arae with 250 observations each. Investigations are ongoing (Udry, private communication) into the possibility of having a reference at the $0.02\,\mathrm{m\,s^{-1}}$ level for an instrument on OWL, while the HARPS GTO programme anyway pushing in this direction will soon help to better characterise the question. In conclusion, a very high radial velocity precision seems possible, but at a very high cost.

There is a significant difference in the case of transiting candidates: now the period and phase are known, and with $e \sim 0$ for short period planets, a series of accumulated measurements can be used to constrain the radial velocity semi-amplitude. With HARPS at a precision of $1\,\mathrm{m\,s^{-1}}$, for short-period planets, it is expected that limits of a few Earth-masses, for $P < 10$ days, can be reached. If the transiting object is larger, then the radial velocity effect will be larger and easier to detect. False positive detections will be the main problem.

(b) Photometric (transit) limits below the Earth's atmosphere are typically a little below the 1% photometric precision, limited by variations in extinction, scintillation and background noise (depending on telescope aperture size), corresponding to masses of about 1 $M_{\rm J}$ for solar-type stars. One main challenge is to reach differential photometric accuracies of around 1 mmag over a wide field of view, in which airmass, transparency, differential refraction and seeing all vary significantly. The situation improves above the atmosphere, and a number of space experiments are planned to reach the 0.01% limits required for the detection of Earth-mass planets. HST can place much better limits on transit photometry than is possible from the ground, as exemplified by HD 209458 (see Sections 2.1.2 and 2.2.1). Simulations have been made by the COROT teams in order to estimate the transit detection threshold due to stellar activity. In the case of a very active star, the detection of an Earth (80 ppm) is not possible. In the case of a quiet star (like the Sun), it is possible if several transits are summed. In the case of COROT, 1.6 $M_\oplus$ is detected after 10–30 transits. Another complication is again false-positives, where statistical effects, stellar activity, and background binaries can all mimic transit events, and which call for independent confirmation of detections in general.

(c) Astrometric measurements do not yet extend below the 1 milli-arcsec of Hipparcos, implying current detectability limits typically above 1–10 $M_{\rm J}$. Even with the expected advent of narrow-field ground-based astrometry at 10 micro-arcsec (e.g. PRIMA), detections would be well short of Earth-mass planets, even within 10 pc. Above the atmosphere, astrometric accuracy limits improve significantly. The studies of Svensson & Ludwig (2005) indicate that for $\log g \sim 4.4$, resulting displacements are around $10^{-7} - 10^{-8}$ AU suggesting, for example, that this effect will not degrade the Gaia measurements, with the exception of nearby (< 100 pc) red giants. Nevertheless, that work treats only the variability caused by the evolution of stellar surface inhomogeneities driven by thermal convection (stellar granulation). At lower temporal frequencies, the variability is much higher (but not yet treatable by hydrodynamic models), caused by magnetic stellar activity, spottiness, and rotation, all of which may make substantial additional contributions to the astrometric (and photometric) variability.

(d) Microlensing searches are not limited by current measurement accuracies for Earth-mass planets, which can produce relatively large amplitude photometric signals (a few tenths of a magnitude or larger), though small amplitude signals are more frequent. The limitations of this method are rather of statistical nature: even if all stars acting as microlenses have planets, only a small subset of them would show up in the microlensed lightcurve, depending on the projected separation and the exact geometry between relative path and planetary caustic. Space measurements help significantly by reducing the photometric confusion effects resulting from observations in very crowded regions (such as the Galactic bulge) which are favoured fields to improve the statistics of detectable events.

2 The Period 2005–2015

2.1 Ground Observations: 2005–2015

There are many ongoing ground-based surveys. At the time of writing, the Planets Encyclopaedia www page (http://www.obspm.fr/encycl/searches.html) lists as either ongoing or planned: 18 radial velocity searches, 15 transit searches, 5 microlensing programmes, 10 imaging/direct detection programmes, 2 radio surveys, and 3 astrometric efforts. An overview of efforts and expected results is given in this section, with a particular focus on the ESA and ESO contributions.

2.1.1 Radial Velocity Searches

A summary of ongoing or planned radial velocity experiments is given in Table 1. It is certainly incomplete, and is intended only to give a flavour for the activity in the field. The vast majority of extra-solar planets discovered so far have been found by radial velocity searches, which have a natural bias for the discovery of massive planets orbiting close to their central star (hot Jupiters). As the surveys continue for longer periods of time they become more and more sensitive to planets having longer periods, and to additional planets in systems in which one hot Jupiter is already known. Dedicated designs have brought spectrographs very close to the practical accuracy limit for ground-based radial velocity searches of $\sim 1\ \mathrm{m\,s^{-1}}$, allowing detection of lower mass planets. HARPS has recently detected a second planet around μ Arae, with a period of 9.5 days, a velocity semi-amplitude of less than $5\ \mathrm{m\,s^{-1}}$ (Santos et al., 2004), and a derived $M \sin i$ of only 14 $M_\oplus$ (about one Uranus mass), making it the lowest mass planet found so far (as of December 2004). A planet of $\sim 17\,M_\oplus$ has been discovered orbiting the M dwarf GJ 436 based on Keck data (Butler et al., 2004), and of $\sim 18\,M_\oplus$ reported for 55 Cnc using HET observations (McArthur et al., 2004).

Another trend is that larger telescopes are being used for the radial velocity searches. As a result the limiting magnitude of such searches has increased from typically $V = 7.5$ a few years ago to $V \sim 12$, with the number of stars thus available for radial velocity study increasing by almost two orders of magnitude. For example, the N2K Consortium is using the Keck, Magellan and Subaru telescopes to track the next 2000 (N2K) closest (<110 pc), brightest, and most metal-rich FGK stars not on current Doppler surveys for new hot Jupiters. Started in early 2004, and with a precision of 4–7 $\mathrm{m\,s^{-1}}$, the first Saturn-mass planet from this survey has recently been reported (Fischer et al., 2005).

Table 5 summarises predictions of the numbers of planets which might be detected by each of the methods discussed in this section, including radial velocity measurements, out to 2008–10. Although such a table is open to misinterpretation and debate (being

Table 1: A summary of completed, operational or planned radial velocity searches (as of December 2004). The table is certainly incomplete, and includes both large successful surveys as well as more uncertain plans; it is intended to give a flavour of the activity in this field.

Name	PI	Telescope	Comments
AAA	Connes	1.52 m	EMILIE will provide $m\,s^{-1}$ accuracy
AFOE	Korzennik	1.5 m	Relocating to Mount Wilson 2.5 m in 2004
AAPS	Butler	3.8 m	Precision 3 $m\,s^{-1}$, to operate to 2010
California & Carnegie	Marcy	3/10 m	Precision 3 $m\,s^{-1}$, plan for dedicated 2.4 m
CES	Kürster	3.6 m	1992–98
Coralie	Mayor	1.2 m	Precision 3 $m\,s^{-1}$, >1650 stars, 200 nights/year
ELODIE	Mayor	1.93 m	Since 1993
Exoplanet Tracker	Ge	11/5 m	Interferometry to $V \sim 12$, test runs 2001–02
Fringing Spectrometer	Erskine	?	Precision 3 $m\,s^{-1}$ targeted
HARPS	Mayor	3.6 m	Precision 1 $m\,s^{-1}$, operational since 2003
HET	Cochran	11 m	Survey of 170 F–K stars $V < 10$ mag
Magellan	–	6.5 m	Observes stars with OGLE transits, since 2003
SARG	Gratton	3.6 m	Binary stars, study effect of metallicity
SOPHIE	Gillet	1.93 m	Precision <3 $m\,s^{-1}$, northern HARPS counterpart
Spectrashift	Amateurs	0.4 m	1.1 m, under construction
TOPS	Hatzes	2 m	First planet recently announced
UCSD/Leiden/Berkeley	Quirrenbach	0.6 m	K-giant survey at Lick CAT
UVES/FLAMES	ESO	8 m	Available to community

sensitive to planetary and instrumental hypotheses) it provides some indication of the development of exo-planet statistics over the next few years.

To derive these estimates for radial velocity observations, the following arguments have been used: (a) during the past year (2003) the number of target stars monitored has at least doubled (HARPS, new Elodie programme, HET, others). New programmes will also probably start in the coming years (e.g. Sophie at OHP). The number of presently known planets with masses in the range $0.5 - 10\,M_{\rm J}$ ('easy planets') can then probably be multiplied by $\sim 3 - 4$; (b) the typical precision is improving, and the number of planets with lower masses will thus further increase. Uncertainty remains on the existence or frequency of low-mass planets in short-period orbits (presently unknown), and in the detailed effects of stellar jitter; (c) the number of long-period planets in the present surveys already ongoing for several years will increase, as the distribution of planet numbers increases with period. However, the maximum mass of detected planets also increases with period, such that many high-mass planets will be found, probably with masses $> 10\,M_{\rm J}$. Earth-masses will be out of reach due to stellar jitter, except maybe for short-P, low-mass transiting planets with P and e fixed, for which a large number of measurements can be stacked at the appropriate phase (see Section 1.3).

More details are included of the ESO contribution, HARPS, since it typifies the state-of-the-art technical and scientific objectives:

HARPS: The Observatoire de Genève together with the Physikalisches Institut der Universität Bern, the Observatoire de Haute-Provence, and the Service d'Aéronomie du CNRS and in collaboration with ESO, developed the HARPS spectrograph installed on ESO's 3.6-m Telescope at La Silla. The instrument is a high-resolution, high-efficiency fibre-fed echelle spectrograph designed to efficiently search for extra-solar planets reaching a precision of 1 $\mathrm{m\,s^{-1}}$ on radial-velocity measurements. Typically, this precision is reached in 1 minute for a $V = 7.5$ G-dwarf star. The long-term precision is ensured by the spectrograph's stability: the spectrograph resides in a pressure- and temperature-controlled vacuum tank, with a drift usually well below 1 $\mathrm{m\,s^{-1}}$ during one night, which can be further corrected using the simultaneous thorium technique. HARPS has been available to the community since October 2003.

For the development of this instrument, the HARPS consortium has been granted 500 guaranteed nights over 5 years (100 nights per year). The HARPS survey is designed to address several specific questions:

(a) only a few of the hundred detected planets have masses less than the mass of Saturn, and due to the present precision of radial velocity surveys the distribution of planetary masses is heavily biased (or completely unknown) for masses less than half the mass of Jupiter. The high precision of HARPS will allow searches for low-mass planets: for a sample of preselected non-active solar-type stars (from the Coralie planet-search sample), the aim is to explore the domain of the mass-function for short-period planets below the mass of Saturn down to a few Earth masses;

(b) in a continuation of the planet-search programmes conducted over ~10 years, a quick screening of a large volume-limited sample of ~1000 still unobserved stars will be performed in order to identify new 'hot Jupiters' and other Jovian-type planets. Increasing the list of 'hot Jupiters' will improve the prospects of finding further stars with a planetary transit among relatively bright stars. Better statistics are needed to identify new properties of the distribution of exo-planet parameters. This part of the programme has already revealed two new short-period planets (Pepe et al., 2004);

(c) a systematic search for planets will be made for a volume-limited sample of slowly-rotating non-binary M-dwarfs closer than 11 pc. Such a survey of very low mass stars should constrain the frequency of planets as a function of stellar mass. Up to now only one planetary system orbiting an M-dwarf is known. For the less massive stars short-period planets of only a few times the mass of the Earth could be detected. Since most of these objects are faint, high efficiency is required. These objects are of prime importance for future astrometric studies to be carried out with the VLTI or SIM;

(d) stars with detected giant planets exhibit an impressive excess of metallicity in contrast to stellar samples without giant planets. The excess of metallicity does not seem related to the mass of the convective zone and probably originates in the chemical composition of the primordial molecular cloud. To add new constraints to the link between star chemical composition and frequency (or properties) of exo-planets, two programmes are being carried out. The first is a search for exo-planets orbiting solar-type stars with notable metal deficiency (for most of them [Fe/H] between -0.5 and -1.0). Among the existing detections of exo-planets only two or three have been found with metallicity in that range. The aim is to estimate the frequency of exo-planets in that domain of metallicity and, if possible, to compare their characteristics (masses, orbits) to planets orbiting metal-rich stars;

(e) the second 'abundance-related' programme aims at exploring the link between stellar metallicity and properties of exo-planets. Visual binaries with solar-type stars of almost identical magnitudes have been selected. For those including giant planets a detailed chemical analysis will be done for both stellar components to search for possible differences in their chemical compositions;

(f) follow-up radial velocity measurements for stars with planetary transits detected by COROT will be made with HARPS (where the photometric transit provides an estimate of the radius of the transiting planet as well as the orbital period and phase). Complementary ground-based spectroscopic measurements with HARPS will constrain the planetary mass and thus the planet mean density. The main scientific return for the planetary programme of the COROT mission will come from this combination of photometric and radial velocity data.

2.1.2 Transit Searches

The transit method aims at detecting the dimming of the stellar light by occultation due to an orbiting planet. Transit experiments offer a number of very important contributions: (i) searches can be conducted over wide fields over long periods (5 years or more), and are therefore potentially efficient at detecting previously unknown systems; (ii) from the ground they are able to detect massive transiting planets, especially the 'hot Jupiters', while from space planets down to Earth-mass or below can be detected; (iii) spectroscopy during the planet transit can yield physical diagnostics of the transiting planets. A summary of ongoing or planned transit experiments is given in Table 2; see also the recent review by Horne (2003). Again, Table 5 summarises predictions of the numbers of planets that might be detected by this method out to 2008–12.

Transit measurements can only detect planets with a favourable orientation of their orbital plane, implying that only a small fraction of planets can ever be detected or monitored using this technique. In particular a nearby census can only reveal a small fraction of existing systems. The probability of viewing a planetary system edge-on depends on the distance of the planet to the central star. For close-in orbits it is about 10%, decreasing for more distant planets. Transit searches therefore try to maximise the number of stars they can observe simultaneously. This can be reached by either small telescopes with wide field of view observing relatively bright stars, or large telescopes providing deep exposures to increase the number of targets monitored. The current transit search surveys therefore group into two classes, using small or larger (> 70 cm) telescopes. Support for the implicit hypothesis that the orbits of planetary systems are randomly distributed in the Galaxy comes from the fact that stellar rotation axes are themselves randomly distributed (obtained by $v \sin i$ distributions, and independently confirmed by magnetic-field orientation studies).

The wide-angle survey teams follow STARE and Vulcan in using small (10 cm) wide-angle (10°) CCD cameras with a pixel size of order 1 arcsec or larger, sacrificing angular resolution to expand the field of view. The faint limit, at $V \sim 12-13$ reaches to $d \sim 300 - 500$ pc, comparable to the disk scale height, so that target fields cover the entire sky, which may contain some 1000 hot transiting Jupiters to this limit (Horne, 2003). The deep surveys use (mosaic) cameras on 1–4 m telescopes, reaching $V \sim 19 - 21$ and $d \sim 4 - 5$ kpc, so that Galactic plane and open cluster fields are primary targets. Horne (2003) predicts up to 200 hot Jupiters per month being discovered by ongoing ground transit surveys in the future (perhaps by the year 2010).

The size of planets detectable from transits with ground-based searches is limited by the Earth's atmosphere (Section 1.3). The photometric precision of typical lightcurves is a little under 1%, which corresponds to about Jupiter-sized planets for solar-type stars. Ground-based surveys are further limited in their time coverage of potential transiting planets by daytime and bad weather periods. The small number of transit surveys operating over more than a few months so far, and the lack of continuous observations on the target fields, are the most likely reason why only few planets have been discovered through transit detections so far, somewhat in contrast with the large number of surveys listed in Table 2. The situation could be significantly improved by ground-based networks of telescopes spanning a range of longitudes to ensure continuous observational coverage of target fields.

The discovery of a temporary dimming of the stellar lightcurve alone is not sufficient to secure the detection of a transiting planet. Grazing eclipsing binary stars, background binaries, brown dwarfs and stellar spots can cause lightcurves similar to transiting planets. Follow-up measurements, in particular radial velocity measurements, and determination of stellar parameters, therefore play an important role in the detection of planetary transits to exclude other causes of light dimming.

Up to now, five confirmed planets have been *discovered* by ground-based transit searches: four using the 1.3 m OGLE telescope, and one with a 10 cm ground-based system (TrES-1). The OGLE experiment (Optical Gravitational Lensing Experiment) uses the 1.3 m Warsaw Telescope at Las Campanas Observatory, Chile. It is equipped with a mosaic of 8 CCDs of 2k×4k each, giving a field of view of 35 arcmin square with 0.26 arcsec/pixel. The telescope is primarily used to search for microlensing events by viewing near the Galactic centre, but significant time (more than three months) was made available for transit searches. It has monitored some

Table 2: A summary of planned or operational transit searches, from space and ground.

Name	D(cm)	FOV (deg)	Comments/Status
Space:			
MOST	15	2.5×2.5	Primarily asteroseismology
COROT	30	2.8×2.8	Asteroseismology and transits
Kepler	95	10×10	Transits: Earth-size planets or larger
Eddington	3×70	4.5×4.5	Transits: not approved
MPF	120	1.2×1.2	Microlensing and transits (previously GEST)
HST	240	0.05×0.05	Specific transit observations possible
Ground:			
PASS	3.6	$15\times$ (28×28)	Observations planned at Tenerife
KELT	4.2	26×26	Tests in New Mexico
WASP-0	6.4	8.8×8.8	Tests on La Palma and in Greece
ASAS-3	7.1	$2\times$ (8.8×8.8)	Operational since Aug 2000 at Las Campanas
SLEUTH (TrES)	10.0	5.66×5.66	Operational since May 2003, Palomar Observatory
STARE (TrES)	10.0	6.03×6.03	Operational since 1999, Tenerife
PSST (TrES)	10.7	5.29×5.29	Operational, Arizona
HATnet	11.0	$5\times$ (8.2×8.2)	HAT-5 operational since Feb 2003 HAT-6 & HAT-7 operational since Sep 2003 HAT-8 operational since Nov 2003 at Mauna Kea
Super-WASP	11.1	$4\times$ (15.9×15.9)	Operational since Apr 2004 on La Palma; second system under construction
RAPTOR-P	14.0	$5\times$ (4.2×4.2)	Under construction in Fenton Hill, New Mexico
Vulcan	12.0	7.04×7.04	Operational since 1999 at Mount Hamilton, California
BEST	20.0	3.1×3.1	Operational since Jul 2001 in Tautenburg, Relocation to OHP (France) in 2004
Vulcan-South	20.3	6.94×6.94	First light 2004, 1 field in Carina observed, Antarctic
APT	50.0	2×3	Operational at Siding Spring, temporarily used
TeMPEST	76.0	0.77×0.77	Operational at McDonald Observatory, Texas
STELLA-2	80.0	0.50×0.50	Commissioning planned for 2005, Tenerife
EXPLORE-OC	101.6	0.25×0.40	Operational in Las Campanas, temporarily used
PISCES	120.0	0.38×0.38	Operational
STELLA-1	120.0	0.37×0.37	Comissioning starts at the end of 2004 at Tenerife
MONET	120.0	various	Under construction at McDonald Observatory, Texas, and in Sutherland, South Africa
ASP	130.0	0.17×0.17	Operational at Kitt Peak
OGLE-III	130.0	0.58×0.58	Operational at Las Campanas, temporarily used
STEPPS	240.0	0.41×0.41	Operational at Kitt Peak, temporarily used
INT	250.0	0.57×0.57	Operational at La Palma, temporarily used
OmegaTranS	260.0	1.00×1.00	Planned for guaranteed time with OmegaCam at VST
EXPLORE-N	360.0	0.57×0.57	Operational at Mauna Kea, temporarily used
EXPLORE-S	400.0	0.61×0.61	Operational at Kitt Peak/CTIO, temporarily used

52 000 disk stars for 32 nights, reporting some 100 transit candidates with periods ranging from 1–9 days (e.g. Udalski et al. 2002a; 2002b) based solely on the dimming of stellar lightcurves. Most of them were quickly identified as stellar binary systems. Radial velocity follow-up for many of the candidate stars was difficult because of the faintness of the stars (down to $I \sim 16$ mag). Nevertheless, four events were confirmed as transiting planets by radial velocity follow-up measurements (Konacki et al., 2003; Bouchy et al., 2004; Pont et al., 2004).

The TrES telescopes belong to the class of small telescopes dedicated to transit searches. All three telescopes of this transit search programme are small aperture (10 cm) wide-field (6°) systems. They are located at Tenerife, Lowell Observatory, and Palomar Mountain, and thus span a range of longitudes (Alonso et al., 2004). Recently, the first planet found by this system has been announced. The discovery is again based on the lightcurves and radial velocity confirmation, showing that small-scale systems indeed have the potential to find transiting planets, providing their observational coverage is sufficiently high.

These examples show the potential of the transit method to find a large number of planets, including small planets, in an unbiased sample of stars. The full potential will be exploited in future space missions, from which Earth-mass planets can be detected (Section 2.2).

In addition to the geometric information derived rather directly from accurate photometric measurements of planetary transits, high-cadence, high S/N spectroscopy of transit events can reveal properties of the planetary atmosphere and exosphere. Extensive work on the first transiting planet, HD 209458b, has shown the level of current photometric and spectroscopic capabilities, principally using HST before the failure of STIS. Ground-based photometry was able to reach a precision of 0.2% (Henry et al., 2000; Charbonneau et al., 2002; Jha et al., 2000; Deeg et al., 2001) while HST/STIS has achieved $\sim 0.01\%$ (Brown et al., 2001). The high-cadence capability of the HST Fine Guidance Sensor (FGS) is also being exploited for transit timing (Schultz et al., 2004).

The use of time-resolved spectroscopy by Charbonneau et al. (2002) showed that the HD 209458b transit was 2.3×10^{-4} deeper when observed at the sodium D lines. Again using STIS, Vidal-Madjar et al. (2003) detect a very large (15%) transit depth at Ly-α, showing that the planet is losing mass. Subsequently the same group (Vidal-Madjar et al., 2004) reported a detection of C and O in the exosphere. In addition to these lines, the possibility exists, in the optical band, of looking for the effects of water (longward of 500 nm) and of Rayleigh scattering in the blue. Moutou et al. (2003) searched unsuccessfully for He I 1083 nm absorption using the VLT with ISAAC. Their upper limit of 0.5% at 3σ for a 0.3 nm bandwidth was limited by the detector fringing properties at this wavelength. An alternative approach is to search for an infrared signature during secondary eclipse. This method, applied by Richardson et al. (2003) which they call 'occultation spectroscopy', searches for the disappearance and reappearance of weak spectral features due to the exo-planet as it passes behind the star. They argue that at the longest infrared wavelengths, this technique becomes preferable to conventional transit spectroscopy. They observed the system in the wing of the strong ν_3 band of methane near 3.6 μm during two secondary eclipses, using the VLT/ISAAC spectrometer at a spectral resolution of 3300 but were unable to detect a signal.

A recent study by Holman & Murray (2005) has shown that for many planets discovered by transit surveys, accurate timing measurements between successive transits (of accuracies between 0.1–100 minutes) will allow for the detection of additional planets in the system (not necessarily transiting) via their gravitational interaction with the transiting planet. The transit time variations depend on the mass of the additional planet, and in some cases Earth-mass planets will produce a measurable effect. This effect is particularly prominent for long-period transiting systems, where the 'perturber' (e.g. an Earth-mass planet) is close to orbital resonance (Agol et al., 2005).

The possibilities for future follow-up studies of this nature at optical and UV wavelengths are seriously compromised by the failure of STIS on HST. Longer wavelength absorption spectroscopy (1–28 μm) should be possible with the NIRSpec and MIRI instruments on JWST provided that these are configured to allow efficient high-cadence and high S/N observations. If HST is followed by another, similar aperture optical UV telescope before 2015, it is likely that strong arguments will be made to equip it to allow STIS-type transit spectroscopy.

CRIRES: CRIRES is a cryogenic high-resolution infrared echelle spectrometer to be installed at the UT1 of the VLT in 2005. It covers the wavelength region 950–5200 nm at a maximum resolution of 100 000 (0.2 arcsec slit). The instrument has been designed for stability, and will be suited for radial velocity studies. Furthermore it may be the most powerful ground-based instrument for transit spectrosocopy in the infrared. Interference from the atmosphere is a severe complication at infrared wavelengths and the gain in resolution of factor 30 with respect to ISAAC will help alleviate this problem. Käufl (2002) discusses the use of OH lines in the K band for the detection of extra-solar planet atmospheres. Hydrocarbons like C_2H_2 or CH_4 are prominent constituents in the atmospheres of Jupiter-like planets in the solar system, and also provide lines in the operating range of CRIRES. The isotope shift of ^{12}CO and ^{13}CO will be well resolved (Boogert et al., 2002, 2004). CRIRES will also allow analysis of the atmospheres of planets, moons and comets in our solar system, some of which have a rich organic chemistry. Performed in close collaboration with the solar system community, a survey at high-spectral resolution will result in a reference library for study of extra-solar planets. Comparsion with measurements from space will result in a much better understanding of the relation between integrated spectrum and local physical conditions in the atmospheres.

2.1.3 Reflected Light

Additional phase-dependent effects, such as the modulation of light reflected from a planet, should also be detectable by accurate photometric satellites with a precision of order 10^{-4}. The method can be used, in principle, both for independent detection of planets, and for studying known hot Jupiters. It might be more effective than transit searches in some cases, because the effect may be observable for a wide range of inclinations, and is not confined to a narrow angle around 90°. The technique is applicable in two cases:

(a) the stellar light reflected by the planet. The ratio of reflected light to the stellar light is of the order of $A(R/2d)^2F(\phi)$, where A is the albedo of the planet, d is the planetary orbital distance, and $F(\phi)$ is a function of the orbital phase, of the order of unity. For a 2.5-day period, Jupiter-radius planet at an orbital separation of $7R_\odot$ around a solar-type star, this ratio is $5 \times 10^{-5}A$, which is almost detectable with COROT or Kepler. For $R = 1.4\,R_{\rm J}$, as in HD 209458, the ratio is $10^{-4}A$. Arnold & Schneider (2004) point out that the shape of the modulation is sensitive to whether the planet has rings.

(b) a stronger effect might be the black-body emission of a close planet. If the planet rotation is synchronised with the orbital motion, one side of the planet faces the parent star all the time, resulting in different temperatures of the two sides of the planet. Estimates suggest differences of up to 1500 K or more, depending on the distance from the star and on the circulation streams in the planetary atmosphere. The hot side of the planet can contribute some fraction of the light of the system, again with a sinusoidal modulation. In the infrared tail of the black-body radiation, the ratio of the planet to star emission could be of the order of 1/400 (Mazeh, private communication), assuming that the far side of the planet is cold. The effect can be seen only in the infrared, and only if there is a large temperature difference between the two sides of the planet.

2.1.4 Microlensing Searches

Microlensing searches for extra-solar planets take advantage of the very characteristic temporal magnification of a (bright) background star, due to a (faint) star-plus-planet system passing in front of it, as seen from Earth. This method is very different from all the other techniques used for planet searching. There are a number of apparent disadvantages: (i) very small probability for a planetary microlensing event, even if all stars have planets (of order 10^{-8} for background stars in the Galactic bulge); (ii) potential planets are much more distant than those found with other techniques (of order a few kpc), which means subsequent more detailed investigations of the planet are close to impossible; (iii) the duration of the planet-induced deviation in the microlensing lightcurve can be very short (typically hours to days), and the measurement is not repeatable: it is a once-and-only event; (iv) lightcurve shapes caused by extra-solar planets can be very diverse and do not always yield a unique planet mass/separation fit; (v) the derived property is not the planet mass, but the mass ratio between host star and planet. However these apparent disadvantages of the microlensing method can largely be 'overcome', and are more than balanced by its many advantages:

(i) no bias for pre-selected nearby host stars: microlensing will provide a fair 'mass-selected' sample of the planet population in the Milky Way;

(ii) no strong bias for planets with large masses: the duration of the planetary signal in the lightcurve is roughly proportional to the square root of the planet mass (with a wide spread); its amplitude, however, is independent of the planet mass to first order (though affected by the finite size of the source star);

(iii) Earth-bound method sensitive down to (almost) Earth-masses: Microlensing is sensitive to lower-mass planets than most other methods (except pulsar searches). In principle, it is possible to even detect Earth-mass planets with ground-based monitoring via microlensing. In practice, however, this would mean extremely high monitoring frequency and photometric accuracy;

(iv) most sensitive for planets within 'lensing zone', which overlaps with habitable zone: microlensing is not sensitive to very close-in planets: the signal would be undistinguishable from a star with the combined mass. In the current mode of operation (planet searching with high monitoring frequency of 'alerted' events), far out planets are not detected either. The most likely detection range is the so-called lensing zone (between 0.6–1.6 Einstein radii), roughly corresponding to projected separations of a couple of AU;

(v) multiple planet systems detectable: The detection of more than one planet per system is certainly possible with microlensing, though its probability is probably another order of magnitude smaller than for a single planet;

(vi) 'instantanous' detection of large semi-major axes possible: The measured (projected) distance between planet and host-star of typically a few AU is, though, only a lower limit to the real semi-major axis;

(vii) detection of free-floating planets (i.e. isolated bodies of planetary mass) possible: space-based searches will have high enough photometric accuracy and monitoring frequency to detect and characterise any existing free-floating planets;

(viii) ultimately best statistics of galactic population of planets: Gravitational microlensing will ultimately provide the best statistics for planets in the Milky Way; it is not bias-free, but the biases in the search technique are of very different character from those of all other methods, can easily be quantified and are more favorable for global (i.e. Galactic) statistics.

These characteristics of the microlensing technique mean that it is complementary to the other search methods.

The first planet detection with the microlensing technique was published in May 2004 (Bond et al., 2004): The OGLE- and MOA-teams detected a clear caustic-crossing microlensing signal in event OGLE-2003-BLG-235 or MOA-2003-BLG-53 which could only be reproduced with a binary-lens model involving a mass ratio of $q = 0.0039^{+11}_{-07}$. The planetary deviation lasted about one week, with a measured maximum magnification of more than a factor of 12. Assuming a low-mass main sequence primary, this would correspond to a planet of about $m_{\rm P} \sim 1.5\,M_{\rm J}$ at a projected separation of about $d \sim 3$ AU.

A summary of ongoing or planned microlensing experiments is given in Table 3. (Stellar) microlensing events continue to be observed at large rates, particularly towards the Galactic bulge (which is the prime search direction due to the high density of background stars). Both MOA and OGLE regularly post their microlensing alerts on their web sites. In the context of exo-planets, specialized networks have been established (PLANET, MicroFUN) which perform follow-up observations of 'alerted' events at high time resolution and look for possible planetary perturbations in the stellar microlensing light curves. In the 2004 observing season, OGLE alone had detected and alerted on more than 600 stellar microlensing events. With the MOA inauguration of a new 1.8-m dedicated telescope in December 2004, more than 1000 stellar microlensing events will be found per season from 2005 onwards.

A number of studies looked into the statistics of planets from microlensing searches. They come in two kinds, either providing detection/exclusion probabilities for planets in individual lightcurves or for ensembles of events:

In the case of MACHO 98–BLG–3, the estimated probability for explaining the data without a planet is $< 1\%$. The best planetary model has a planet of $0.4 - 1.5\,M_\oplus$ at a projected radius of either 1.5 or 2.3 AU (Bond et al., 2002).

Very high magnification events are well-suited for showing signatures of planets, because the relative track is very close to the central caustic which should be slightly perturbed by the existence of any planet (at the same time, such planets are difficult to characterise uniquely): In the case of MOA 2003–BLG–32 = OGLE 2003–BLG–219 (Abe et al., 2004), with a peak magnification of more than 500, continuous observations around the maximum did not show any planetary signature. This enabled the authors to put very stringent limits on the probability of a companion: planets of $m_{\rm P} = 1.3\,M_\oplus$ are excluded from more than 50% of the projected annular region from $\sim 2.3 - 3.6$ AU surrounding the lens star, Uranus-mass planets from 0.9–8.7 AU, and planets 1.3 more massive than Saturn are excluded from 0.2–60 AU.

The best published statistical limits on the frequency of Jupiter-mass planets from (lack of) microlensing signatures can be found in Gaudi et al. (2002), based on the first five years (1995–99) of PLANET team data. They concluded that less than 33% of the M-dwarfs in the Galactic bulge have Jupiter-mass companions with a projected separation between 1.5–4 AU. Many more stellar events have been monitored subsequently, and improved limits should become available soon.

Table 3: A summary of completed, operational or planned microlensing searches.

Name	PI	Telescope	Comments
MACHO	Alcock	1.3 m	1992–99: $\sim 10^7$ stars in LMC, $\sim 10^7$ in Milky Way
MOA	Network	0.6 m	1.8 m with 2° field planned for 2005
MPS	Bennett	1.9 m	
PLANET	–	0.6/0.9/1.0/2.2 m	Collaboration of 16 institutes, 10 countries
MicroFUN	–	multiple	Microlensing follow-up
MPF/GEST	Bennett	1–1.5 m	Proposal for NASA Discovery Mission

The availability of the VST may soon provide a means for ESO to support a massive microlensing search for planets (cf. Sackett 1997, Appendix C of the Final report of the ESO Working Group on the Detection of Planets).

A space-based microlensing mission (MPF/GEST) is discussed in Section 2.2.3.

2.1.5 Astrometry

The principle of planet detection with astrometry is similar to that underlying the Doppler technique: the presence of a planet is inferred from the motion of its parent star around the common centre of gravity. In the case of astrometry the two components of this motion are observed in the plane of the sky; this gives sufficient information to solve for the orbital elements without $\sin i$ ambiguity. Astrometry also has advantages for a number of specific questions, because this method is applicable to all types of stars, and more sensitive to planets with larger orbital semi-major axes. Astrometric surveys of young and old planetary systems will therefore give unparalleled insight into the mechanisms of planet formation, orbital migration and evolution, orbital resonances, and interaction between planets. Interferometric techniques should improve astrometric precision well beyond current capabilities.

Specific applications are:

(a) mass determination for planets detected in radial velocity surveys (without the $\sin i$ factor). The radial velocity method gives only a lower limit to the mass, because the inclination of the orbit with respect to the line-of-sight remains unknown. Astrometry can resolve this ambiguity, because it measures two components of the orbital motion, from which the inclination can be derived;

(b) confirmation of hints for long-period planets in radial velocity surveys. Many of the stars with detected short-period planets also show long-term trends in the velocity residuals (Fischer et al., 2001). These are indicative of additional long-period planets, whose presence can be confirmed astrometrically;

(c) inventory of planets around stars of all masses. The radial velocity technique works well only for stars with a sufficient number of narrow spectral lines, i.e., fairly old stars with $M < 1.2\,M_\odot$. Astrometry can detect planets around more massive stars and complete a census of gas and ice giants around stars of all masses;

(d) detection of gas giants around pre-main-sequence stars, signatures of planet formation. Astrometry can detect giant planets around young stars, and thus probe the time of planet formation and migration. Observations of pre-main-sequence stars of different ages can provide a test of the formation mechanism of gas giants. Whereas gas accretion on $\sim 10\,M_\oplus$ cores requires $\sim 10\,\mathrm{Myr}$, formation by disk instabilities would proceed rapidly and thus produce an astrometric signature even at very young stellar ages;

(e) detection of multiple systems with masses decreasing from the inside out. Whereas the astrometric signal increases linearly with the semi-major axis a of the planetary orbit, the radial velocity signal scales with $1/\sqrt{a}$. This leads to opposite detection biases for the two methods. Systems in which the masses increase with a (e.g., υ And) are easily detected by the radial velocity technique because the planets' signatures are of similar amplitudes. Conversely, systems with masses decreasing with a are more easily detected astrometrically;

(f) determine whether multiple systems are coplanar or not. Many of the known extra-solar planets have highly eccentric orbits. A plausible origin of these eccentricities is strong gravitational interaction between two or several massive planets. This could also lead to orbits that are not aligned with the equatorial plane of the star, and to non-coplanar orbits in multiple systems.

Astrometric observations by interferometry are based on measurements of the delay $D = D_{\rm int} + (\lambda/2\pi)\phi$, where $D_{\rm int} = D_2 - D_1$ is the internal delay measured by a metrology system, and ϕ the observed fringe phase. Here ϕ has to be unwrapped, i.e., not restricted to the interval $[0, 2\pi)$. In other words, one has to determine which of the sinusoidal fringes was observed. This can, for example, be done with dispersed-fringe techniques (Quirrenbach, 2001). D is related to the baseline $\vec{B}$ by $D = \vec{B} \cdot \hat{s} = B \cos\theta$, where $\hat{s}$ is a unit vector in the direction towards the star, and θ the angle between $\vec{B}$ and $\hat{s}$. Each data point is thus a one-dimensional measurement of the position of the star θ, provided that the length and direction of the baseline are accurately known. The second coordinate can be measured with a separate baseline at a roughly orthogonal orientation. The photon noise limit for the precision σ of an astrometric measurement is given by $\sigma = (1/\mathrm{SNR}) \cdot (\lambda/(2\pi B))$. Since high signal-to-noise ratios can be obtained for bright stars, σ can be orders of magnitude smaller than the resolution λ/B of the interferometer. For example, the resolution of SIM ($B = 10\,\mathrm{m}$) is about 10 milli-arcsec, but the astrometric precision should approach 1 micro-arcsec; for PRIMA, $B = 200\,\mathrm{m}$, the resolution is 2 milli-arcsec, and the astrometric precision should approach 10 micro-arcsec.

Because of the short coherence time of the atmosphere, precise astrometry from the ground requires simultaneous observations of the target and an astrometric reference. In a dual-star interferometer, each telescope accepts two small fields and sends two separate beams through the delay lines. The delay difference between the two fields is taken out with an additional short-stroke differential delay line; an internal laser metrology system is used to monitor the delay difference (which is equal to the phase difference multiplied with $\lambda/2\pi$). For astrometric observations, this delay difference ΔD is the observable of interest, because it is directly related to the coordinate difference between the target and reference stars; it follows that $\Delta D \equiv D_t - D_r = \vec{B} \cdot (\hat{s}_t - \hat{s}_r) = B(\cos\theta_t - \cos\theta_r)$, where the subscript t is used for the target, and r for the reference. To get robust two-dimensional position measurements, observations of the target with respect to several references and with a number of baseline orientations are required.

Measurements of the delay difference between two stars give relative astrometric information; this means that the position information is not obtained in a global reference frame, but only with respect to nearby comparison stars, which define a local reference frame on a small patch of sky. This approach greatly reduces the atmospheric errors, and some instrumental requirements are also relaxed. The downside is that the information that can be obtained in this way is more restricted, because the local frame may have a motion and rotation of its own. This makes it impossible to measure proper motions. Moreover, all parallax ellipses have the same orientation and axial ratio, which allows only relative parallaxes to be measured.

Specific instrument approaches are discussed in Section 2.1.6 (NAOS-CONICA, Planet Finder, PRIMA) and Section 2.2.2 (Gaia, SIM, etc.).

No planets have been discovered using this technique to date.

2.1.6 Direct Detection

The light coming from an extra-solar planet is much fainter (of order 10^9 in the optical, and a factor 10–100 less in the infrared) than the signal from the star. Therefore the challenge is to build instruments that are able to provide extremely high contrast and spatial resolution. The different approaches are summarised below and in Table 4. The first direct detection of a young planet may already have been achieved by a team using NACO on the VLT. An object detected close to 2MASS WJ1207334–393254 is either a planet or possibly a brown dwarf (Chauvin et al., 2004). Regardless of the exact nature of this particular object, it is likely that imaging of more massive, young extra-solar planets will become more feasible in the near future.

A number of programmes are using, or planning to use, interferometry to achieve high spatial resolution. Destructive interference can be used to remove most of the light from the central star (nulling). ESA and ESO are collaborating on a

Table 4: A summary of planned or operational direct searches. Space astrometry and transit searches are covered elsewhere, and are excluded from this table. The first category are interferometric or multi-telescope projects; the second are single telescope direct methods; the third are in the radio or sub-mm.

Name	PI	Telecope	Comments
Darwin	ESA	3×3.5 m	IR interferometer in L2, launch goal 2015
TPF-I	NASA	several 3–4 m	IR interferometer launch before 2020
AMBER	Petrov	VLT	Operations recently started
ANI	Hinz	6.5 m	Tests on nulling in 1997–98
AIC	Gay	1.5 m	First test runs in 1997
BLINC	Hinz	6.5 m	Instrument ready for use at MMT
Carlina	Le Coroller	hypertelescope	First fringes with 2×24 cm mirrors, 2004
Keck i/f		2×10 m	First fringes 2001, shared risk science 2002
KEOPS		1 km array	Time frame 2015+
LBT		2×8.4 m	First light planned for Dec 2004
PTI	Colavita	3×0.4 m	K-band stellar interferometer, $\sim$100 μas
VLTI	Glindemann	8/1.8 m	MIDI operational since 2003
TPF-C	NASA	4–6 m	Visible light coronograph launch 2014
CHEOPS	Feldt	8 m	Proposal for VLT instrument
EXPORT	Eiroa	several	Observations in 1998/99
JWST	NASA	6.5 m	IR-optimised telescope in L2, launch 2011
Lyot Project	Oppenheimer	3.6 m	First light April 2003
MIRLIN	Ressler	3, 5, 10 m	Operational since 2001
Trojan	Caton	0.45/0.7 m	2-colour photometry of 20 eclipsing binary
ALMA	ESO	64×12 m	First light planned for 2007
LOFAR		100 antennae	Decametric emission: initial 2006/full 2008
Nancay		radio arrays	
Pulsar Planets	Wolszczan	305 m	Planets around PSR B1257+12

nulling demonstrator for Darwin called GENIE which will be used on the VLT. Other searches use a coronographic approach to block out the star's light. The Lyot project's coronograph has now been declared fully operational and will conduct a survey of 300 nearby stars.

NAOS-CONICA: NAOS-CONICA (NACO) is installed on UT3 at the VLT. It is an adaptive optics system working in the 1–5 μm range, with a Shack-Hartmann wavefront analyser operating in the visible or near-infrared. The instrument is equipped with a large collection of broad- and narrow-band filters for imaging, and a set of grisms for low-dispersion spectroscopy. It also features a polarimetric system. In good conditions, with a bright reference star, a Strehl ratio of ~ 0.5 is achievable.

Two modes are of special interest for planetary observations: (1) a coronographic mode: a classical Lyot-type instrument with a circular focal spot (of 0.7 or 1.4 arcsec) is used together with an undersized pupil mask. A four quadrant phase mask (which introduces a shift of π to the wavefront) is being commissioned. It reduces the light of the central star by a factor of ~ 70, and permits observations within

0.35 arcsec of the centre, i.e. much closer than with a classic mask; (2) simultaneous differential imaging over 5×5 arcsec^2: four images are obtained simultaneously through 3 narrow-band filters. Two are taken in the 1.625 μm methane feature, and the two others at 1.575 and 1.600 μm, outside the spectral line. The data are registered simultaneously in the four channels, and the point-spread function (including all its residual aberrations, and the speckles, including super-speckles) are identical in all four images. This mode was designed to search for methane-rich objects near very bright stars, with a contrast of 50 000 accessible. With these characteristics, a Jupiter-like planet in a Jupiter-like orbit around a very nearby star (within 5 pc) should be just detectable at its largest elongation. Detection performances are limited by uncorrected phase residuals (mainly low-order aberrations). NACO should be considered as a prototype permitting the study of novel techniques that will be used in dedicated instruments such as ESO's Planet Finder.

Planet Finder: The next step beyond the VLT AO facility NAOS-CONICA (NACO) would be a dedicated VLT instrument optimised for the detection of extrasolar planets. Two independent design studies are currently underway for such a Planet Finder instrument at the VLT. The prime goal is to gain at least an order of magnitude with respect to NACO in the detection of faint objects very close to a bright star, ideally reaching giant planets. Much higher Strehl ratios than NAOS, around 0.9 in the K-band, are targetted. Planet Finder will combine high-order adaptive optics with differential detection techniques; multi-waveband imaging, integral-field spectroscopy, and imaging polarimetry are foreseen for the focal plane instruments. Planet Finder could become operational around 2009. A review board for the assessment of the Phase A studies met on 16–17 December 2004.

Planet Finder may discover giant planets in different phases of their evolution. During the ongoing contraction and accretion phases, the internal luminosity of these planets exceeds the reflected light contribution by several orders of magnitude, e.g. a Jupiter mass planet will be 10^3 times brighter at 1 Myr than at 1 Gyr. This raises the possibility of detecting young planets around the closest young stars, in spite of their relatively large distances. Planet Finder will also search for old planets in the Solar neighbourhood. The S/N for the detection of exo-planets drops rapidly with distance, due to the combined effects of inverse-square brightness losses and the reduction in stellar-planet angular separation. The most promising targets for old systems are therefore within 5–10 pc, exploring the range in separation down to $\simeq 3-5$ AU. For this reason, possible targets for Planet Finder may be found among stars known to have planetary systems from high-precision radial velocity surveys. Even more promising is the synergy with planet searches using astrometric perturbations: giant planets detected by Planet Finder should give a signal in the tens of milli-arcsecond range, clearly measurable with PRIMA and/or future space missions (SIM, Gaia). This will provide an independent estimate of planetary masses.

The detailed science cases will probably differ between both groups because of different AO system performances and focal instruments. In the French-led proposal,

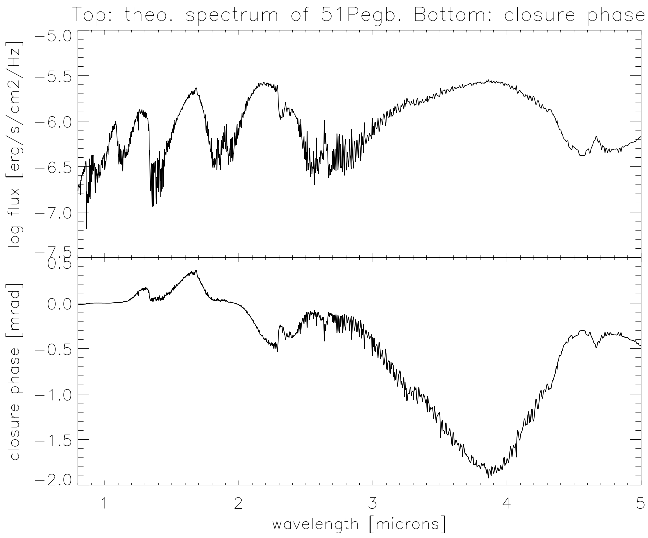


Figure 3: Spectral signal of planet in the closure phase. Top panel: theoretical spectrum of the giant irradiated planet orbiting the solar-like star 51 Peg (Sudarsky et al., 2003). Clearly visible are CO and H_2O absorption bands in the near-IR. Bottom panel: closure phases in milli-radian based on the theoretical spectrum of 51 Peg b as well as of the host star and a simulated observation with the near-IR instrument AMBER at the VLTI using the three telescopes UT1, UT3 and UT4 (baseline lengths 102 m, 62 m, and 130 m). It is evident that the spectrally-resolved closure phases contain a wealth of spectral information of the planet.

typical targets are: (a) stars in young associations (more than 100 candidates), which will be looked at much closer than with NACO (with an interference coronagraph, at 1–2 λ/D, achievable contrast $> 10^{-5}$); (b) close-by solar-type stars at moderate ages (1–2 Gyr): contrast: a few 10^{-5}; about 200 objects; for some nearby objects performances should be much better; (c) late-type stars of all ages: with better performances on the youngest and closest ones; (d) other science: disks and stellar environments. In the German-led proposal (CHEOPS) the primary goals are to find mature (old, Jupiter-like) planets in nearby systems (within 15 pc), with polarimetry possible; and young, still-warm planets in the nearest star-forming regions (within 100 pc) with an integral-field spectrograph operating in the J and H bands. Secondary goals are to observe brown dwarfs, young stellar object disks, debris disks, etc.

PRIMA: The ESO VLT Interferometer consists of four 8 m Unit Telescopes and four moveable 1.8 m Auxiliary Telescopes, which can form baselines up to 200 m in length. The PRIMA (Phase-Reference Imaging and Micro-Arcsecond Astrometry, Quirrenbach et al. (1998)) facility will implement dual-star astrometry at the VLTI; it is expected to become operational in 2007. Its goal is to measure the masses and orbital inclinations of planets already known from radial velocity surveys. In addition, a survey with PRIMA will be conducted to establish the frequency of planets along the main sequence and through time.

The principles of interferometric astrrometry are summarised in Section 2.1.5. Differential phase observations with a near-IR interferometer offer a way to obtain spectra of extra-solar planets. The method makes use of the wavelength dependence of the interferometer phase of the planet/star system, which depends both on the interferometer geometry and on the brightness ratio between the planet and the star. The differential phase is strongly affected by instrumental and atmospheric dispersion effects. Difficulties in calibrating these effects might prevent the application of the differential phase method to systems with a very high contrast, such as extra-solar planets. A promising alternative is the use of spectrally resolved closure phases, which are immune to many of the systematic and random errors affecting the single-baseline phases.

Figure 3 shows the predicted response of the AMBER instrument at the VLTI to a realistic model of the 51 Peg system, taking into account a theoretical spectrum of the planet as well as the geometry of the VLTI. Joergens & Quirrenbach (2004) have presented a strategy to determine the geometry of the planetary system and the spectrum of the extra-solar planet from such closure phase observations in two steps. First, there is a close relation between the nulls in the closure phase and the nulls in the corresponding single-baseline phases: every second null of a single-baseline phase is also a null in the closure phase. This means that the nulls in the closure phase do not depend on the spectrum but only on the geometry, so that the geometry of the system can be determined by measuring the nulls in the closure phase at three or more different hour angles. In the second step, the known geometry can then be used to extract the planet spectrum directly from the closure phases.

ALMA: ALMA is an interferometer in the mm-wavelength range, which will consist of sixty-four 12 m diameter antennae located in northern Chile, at 5050 m altitude. The antennae can be spaced from a compact configuration with a maximum separation of 150 m to a very extended configuration where the maximum spacing is 16 km, providing a resolution of 10 milli-arcsec at shortest wavelengths. The receivers will cover the atmospheric windows in the 35–1000 GHz range (350 μm – 7 mm) with a bandwidth of 8 GHz in two polarizations, and a resolution of 32000 channels. ALMA will be powerful for studying the disks around young stars, able to image such disks out to several hundred parsecs, providing density and temperature profiles (through measurements of thermal dust emission), and providing constraints on disk dynamics and chemistry (through measurements of spectral lines). In the case of protoplanetary disks, ALMA will be able to image gaps and holes caused by protoplanets.

In terms of direct detection of the planet themselves, however, ALMA is rather limited. At its best resolution (widest configuration), the system will be able to resolve a Jupiter-like planet from its star out to 100–150 pc. The main limitation comes from the flux of the planet. The best frequency for planet observation, which optimises the combination of expected detector noise characteristics, the spectrum of the objects, and the site characteristics, is at 350 GHz. The flux density of the planet is directly related to their temperature, size and distance as $F_{350} = 6.10^{-8}\, T R_{\rm J}^2/D^2$, where the distance D is in pc, R_J the radius expressed in Jupiter units, and T the temperature in K. Together with the expected sensitivity performances of ALMA, this indicates that a Jupiter would be detectable only out to about 1 pc. In the case of a 'hot Jupiter' ($R = 1.5\,R_J$, $T = 1000\,K$), this limit is pushed to a few parsecs, but still not far enough to actually encompass any useful star. On the other hand, a proto-Jupiter (with $R = 30\,R_J$ and $T = 2500\,K$) would be detectable in a matter of minutes to hours out to several tens of parsecs.

The contrast between the star and the surrounding bodies, a critical factor at shorter wavelengths (visible–infrared), becomes an advantage in the case of ALMA. The contrast factor is of the order of 1000, which is well within the dynamic range of the detectors, and the bright central source helps maintaining the optimal coherence of the interferometer. So, while ALMA is not expected to contribute significantly to the study of mature planets, its contribution will be very significant for studying early stages of planet formation, from nebula to protoplanet.

2.1.7 Other Searches

The upper right-hand section of Figure 1 indicates some miscellaneous search methods. Jupiter's magnetosphere is known to produce strong emission of radio waves. These decametric bursts are targeted by a number of collaborative efforts in the radio community, as summarised in Table 4. As noted in Section 2.2.2, Gaia might also detect a few protoplanetary collisions photometrically (Zhang & Sigurdsson, 2003), although whether they could ever be recognised as such, buried within such a vast volume of other variables, has not been assessed.

2.2 Space Observations: 2005–2015

In the near-term future of space missions, there are two principal detection approaches: transits (exemplified by the COROT, Kepler and Eddington missions), and astrometry (exemplified by Gaia and SIM). A non-approved concept, MPF (originally GEST), uses microlensing to expand on the parameter space for which statistical information on planet frequency would be provided.

2.2.1 Space Transit Measurements: COROT, Kepler and Eddington

COROT: COROT is a French-European-ESA collaboration, led by CNES, comprising a 27 cm telescope with a CCD camera, with a launch planned for June 2006. After MOST, it will be the second satellite dedicated to long-term high-accuracy photometric monitoring from space. COROT will combine the study of asteroseismology with the search for exo-planetary transits. The observation of 60 000 stars (12 000 stars simultaneously for 150 days each) is expected to result in the detection of a few hot telluric planets.

As a general remark, which applies to the other predictions in this section, as well as to the radial velocity and ground-based transit searches discussed previously, it should be noted that the expected rate of exo-planet detection is difficult to quantify, given both their unknown frequency of occurrence, and detection uncertainties due to stellar activity.

The numbers in Table 5 are based on the number of dwarf stars in the COROT fields, the mass and period distribution of known exo-planets, the probability of transits, the fact that no more than 1 short-period exo-planet per star is expected, and the expected accuracy of COROT as a function of magnitude. Table 3 in Bordé et al. (2003) assumes one planet per dwarf star, and a uniform orbital distribution law. This leads to a significantly larger number of predicted detections, and is presumably an overestimate of the actual number of planets expected (as they also note). In practice, the critical factor in all these predictions is the unknown number of low-mass planets per star.

Kepler: improved prospects for photometric transit detections will come with NASA's Kepler mission, due for launch around 2007. Kepler is a 0.95 m aperture, differential photometer with a 105 square degree field of view. It focuses on the detection of Earth-size planets or larger in or near the habitable zone of a wide variety of stellar spectral types, monitoring some 10^5 main-sequence stars brighter than 14 mag. Detection of some 50–640 terrestrial inner-orbit planet transits are predicted, depending on whether their typical radii lie in the range $R \sim 1.0 - 2.2 R_{\rm E}$, determining the distribution of sizes and orbital characteristics. Kepler will assist the preparation of future programmes like SIM and Darwin/TPF by identifying the common stellar characteristics of host stars, and defining the volume of space needed to search.

The numbers in Table 5 are taken from the Kepler www site, and are based on the following assumptions: 100 000 main-sequence stars observed with a precision of better than $\sim 5 \times 10^{-5}$; typical variability of 75% of the stars is similar to that of our Sun; most main-sequence stars, including binaries, have terrestrial planets in or near the habitable zone; on average, two Earth-size or larger planets exist between 0.5–1.5 AU; transit probability for planets in the habitable zone is 0.5% per planet; the transit is near grazing in a 1-year orbit; each star has one giant planet in an outer orbit; on average 1% of the main-sequence stars have giant planets in orbits shorter than 1 week and comparable numbers in periods of 1–4 weeks and 1–12 months; mission life time of 4 years. Results for giant planets are expected around 2007, with those on terrestrial planets (which will require more careful verification) around 2010.

Eddington: ESA's Eddington mission was originally proposed for launch around 2008. It entered ESA's science programme as a 'reserve' mission, was approved in 2002, but cancelled in November 2003 due to overall financial constraints. The Eddington payload was composed of three identical, co-aligned telescopes with a $\simeq 0.7$ m aperture and identical 3×2 mosaic CCD cameras, a total collecting area of $\simeq 0.75$ m^2 and a field of view of $\simeq 20$ deg^2. Each telescope had a slightly different bandpass, allowing colour information to be derived for high S/N transits.

The baseline lifetime was 5 years (extended operations possible), of which three would be dedicated to a single long observation (currently baselined in Lacerta), and two would be used for short (one to a few months) observations of other fields. Planet searches were to be conducted during the three years observation, in $\sim 10^5$ stars, of which $\sim 10^4$ would be observed with sufficient accuracy to detect Earth-like planets. During the shorter observations, a further $\sim 4 \times 10^5$ stars would be searched for planets, allowing many shorter-period planets to be discovered.

The numbers in Table 5 are the results of detailed Monte Carlo simulations, which assume a 'standard' planet function of the form $f(a, m|M) \propto a^\alpha m^\beta M^\gamma$ where a is the orbital radius of the planet, m its mass, and M the mass of the parent star, and using the mass-radius relationship obtained from solar system objects. The simulations used $\gamma = 0$, i.e. the planet function is independent of the stellar mass. As both the Doppler planet population and the solar system objects are consistent with $\alpha = -1$, $\beta = -1$, the simulations have also used $f(a, m) \propto a^{-1}m^{-1}$ normalised to 0.01 hot Jupiters per star (as derived from the Doppler surveys). In this assumption, each star has 0.25 normal Jupiters ($r > R_{\rm J}$), 0.01 hot Jupiters ($r > R_{\rm J}$, $P = 3 - 5$ day), 0.85 Earths ($R > R_\oplus$) at any orbital distance, and 0.07 'habitable planets' (with liquid water temperatures). This is considered as a conservative mass function, as the typical star probably has fewer rocky planets than the solar system. Also, the simulations are stopped at $R = 1R_{\rm J}$ (because of the emphasis on the smaller planets), so that the number of gas giants is under-predicted. The result of the Monte Carlo simulation predicts, for the single 3-year observation: 14 000 planets in total (in 12 500 planetary systems), of which 8000 hot planets, of which 5600 with $R > 5R_\oplus$, 660 Earths ($0.5 < R < 2.0R_\oplus$); 160 habitable zone planets, of which 20 'Earths'. A larger number of hot Jupiters would also be found in the short (asteroseismology) observations. Predictions for multiple systems depend sensitively on the assumed distribution of relative orbital inclinations.

The following missions, not dedicated to transits, can also be noted:

HST: although suitably placed above the atmosphere such that low-mass planets could be detected by HST using this technique in principle, HST is not a dedicated transit discovery instrument, and its discovery efficiency is constrained by its limited field of view, and available observing time. Any searches using HST will therefore likely be restricted to observations of especially high-surface density regions. Observations of 47 Tuc (34 000 main-sequence stars monitored for 8.3 days) failed to detect planets (Gilliland et al., 2000), whereas 17 would have been expected based on radial velocity surveys. This non-result is currently attributed to effects of metallicity (Gonzalez, 1998), ultraviolet evaporation (Armitage, 2000), or collisional disruption (Bonnell et al., 2001) of the protoplanetary disks in this crowded stellar environment. An advance in transit statistics should come from observations of the Galaxy bulge with HST by Sahu et al., monitoring 100 000 stars to $V = 23$ over 7 days in February 2004, with results expected in spring 2005.

Nevertheless HST, and its successor JWST, have considerable potential for follow-up observations of transiting systems discovered by other methods, for example by Kepler. This issue is developed further in Section 4.

MOST: the Canadian satellite MOST is a 15 cm telescope launched on 30 June 2003. Dedicated to the long-term photometric monitoring of a small number of stars primarily for asteroseismology studies, it has a photometric performance just a factor of 2 better than from ground (Matthews et al., 2004). Although with limited transit discovery potential, it will nevertheless aim to detect reflected light of a few known hot Jupiters.

2.2.2 Space Astrometry Missions: Gaia and SIM

As noted previously, astrometric planet detection involves detecting the system's photocentric motion on the plane of the sky, in the same way that radial velocity detection involves detecting the system's photocentric motion along the line of sight. The amplitude of the displacement, and therefore the system's detectability, can be characterised by the system's 'astrometric signature', $\alpha = (M_{\rm Planet}/M_{\rm star}) \cdot (a/d)$. This signature is measured in arcsec when the orbital radius a is measured in AU and the distance d is measured in pc. Astrometric measurements can provide the planetary mass directly rather than $M \sin i$ (as provided by radial velocity techniques) if d is determined and if $M_{\rm star}$ is estimated from stellar evolutionary theory.

Figure 4 shows the astrometric signature versus orbital period for the known exoplanets, where the size of the circles indicates the planetary mass. The horizontal line at the top of the figure indicates the Hipparcos astrometric accuracy, and shows immediately why Hipparcos was unable to detect new planetary systems. Nevertheless, Hipparcos data was useful for placing some constraints on the masses of planet candidates (Zucker & Mazeh, 2001).

Gaia (ESA) and SIM (NASA) are two very different approaches to space astrometry, both approved and under development:

Gaia: Gaia is a scanning, survey-type instrument, with a launch around 2011 (Perryman et al., 2001). Its detectability domains are shown in Figure 4: periods below about 0.2 yr will not be detectable because of the relatively long times between successive observations dictated by the scanning law, while periods longer than about 12 yr will result in photocentric motions indistinguishable from rectilinear motion over the mission's measurement duration (about 5 years). As seen in the figure, Gaia will therefore contribute substantially to the large-scale systematic detection of Jupiter-mass planets (or above) in Jupiter-period orbits (or smaller); some 10–20 000 detections out to 150–200 pc are expected (Lattanzi et al., 2000; Sozzetti et al., 2001), including confirmation of most of the (longer-period) radial velocity detections known to date. Planetary masses, M, rather than $M \sin i$, will be obtained. Full orbital parameters will be obtained for some 5000 (higher S/N) systems. Relative inclinations can in principle be obtained for multiple systems with favourable orbits (Sozzetti et al., 2001), important for studies of formation scenarios and orbital stability of multiple systems. Some 4–5000 transit systems, of the hot-Jupiter type, might also be detected (Robichon, 2002). Gaia might also detect a handful of protoplanetary collisions photometrically (Zhang & Sigurdsson, 2003). Gaia cannot observe systems at epochs other than those determined by its fully deterministic scanning law, and will not detect planets with masses much below 10–20 $M_\oplus$ unless such systems exist within 10–20 pc.

SIM: SIM is a pointed interferometer with a launch around 2010 (Danner & Unwin, 1999): accuracies of a few micro-arcsec down to 20 mag are projected. Such faint observations will be expensive in terms of observing time, and brighter target stars are likely to be the rule. Of 15 key projects and mission scientist programmes currently studied, three focus on planetary systems: (1) A Search for Young Planetary Systems (Beichman): this will survey 200 stars with ages from 1–100 Myr (mostly in star-forming regions at 125–140 pc, but including TW Hya at 50 pc) which expects to find anywhere between 10–200 planets, depending on whether the occurrence rate is the canonical 5–7 % from current radial velocity surveys, or 100 % of all young stars. The survey will be sensitive to $M_{\rm J}$ planets at orbital distances of 1–5 AU. (2) Discovery of Planetary Systems (Marcy): this will focus on searches for 1–3 $M_\oplus$ planets within 8 pc, and for 3–20 $M_\oplus$ planets within 8–30 pc. The survey is also considered as a reconnaissance for TPF. Target stars will be selected from ongoing surveys of the nearest 900 GKM main-sequence stars in the northern hemisphere with the Lick 3-m and the Keck 10-m telescopes, the nearest 200 GK stars in the south with the AAO 3.9-m, and the planned 6.5-m Magellan survey extending to a further 600 GKM stars in the south. (3) Extra-Solar Planet Interferometric Surveys

(Shao): this major SIM survey programme comprises a deep survey of about 75 nearby main-sequence stars within about 10 pc of the Sun, of which one third are G dwarfs and the remainder are inactive main-sequence stars of other spectral types (mostly K and M but including a few A and F). Over the mission lifetime, each target will be observed some 70 times, each of twenty 1-minute observations resulting in a final accuracy of about 1 micro-arcsec. Each pointing will be accompanied by the observation of typically 28 additional bright nearby stars (within 25 pc), with single 1-minute observations leading to some 2000 stars observed with accuracies of about 4 micro-arcsec. These will be from diverse types: all main-sequence spectral types, binaries, a broad range of age and metallicity, dust disks, white dwarfs, planets from radial velocity surveys, etc. Preparatory programmes for this survey include radial velocity monitoring and adaptive optic imaging. The total expected number of new detections from SIM, for any given planetary mass and orbital radius is again not straightforward to predict, and depends on the (unknown) mass distribution of exo-planets versus orbital radius at $a \sim 1$ AU. Estimates are given in Table 5.

The NASA SMEX proposal AMEX (which followed on from the FAME study) aimed at 150 micro-arcsec accuracy at 9 mag and 3 milli-arcsec at 15 mag and, with a proposed launch in 2007–08, would have provided limited prospects for planet detection through the comparison of proper motions with Hipparcos, including some 600 detections to 30 pc down to K5V stars, and transits to V =11 mag. AMEX was not selected by NASA in 2003. In mid-2004 NASA announced the selection of nine studies for future mission concepts within its 'Astronomical Search for Origins Program', including the 'Origins Billion Star Survey' (OBSS) focussing on a census of giant extra-solar planets using the principles of Gaia. If OBSS is selected, its contribution to astrometric exo-planet research would not surpass those of Gaia.

The Japanese mission JASMINE, and a potential prototype nano-JASMINE, have been under discussion at a low level in Japan for several years (Gouda et al., 2002). Originally conceived as a mini-Gaia but able to concentrate on the Galactic centre by operating in the infrared, the mission's technical feasibility has been improved in the past few months (although its scientific niche has been weakened) with the move to CCD detector technology.

2.2.3 Space-Based Microlensing: MPF

Proposals for exo-planet detection through their microlensing signatures have been made. GEST (Galactic Exo-Planet Survey Telescope (Bennett & Rhie, 2002)) was proposed for a NASA mission in 2001–02 (a Survey for Terrestrial Exo-Planets (STEP) was also submitted to NASA's Extra-Solar Planets Advanced Concepts Program at the same time). It was not selected in 2002, but was re-submitted during 2004 under the name of Microlensing Planet Finder (MPF), using HgCdTe and Si-PIN detectors in place of the earlier CCDs (Bennett et al., 2004).

A 1.2-m aperture telescope with a 2 deg^2 field of view continuously monitors 10^8

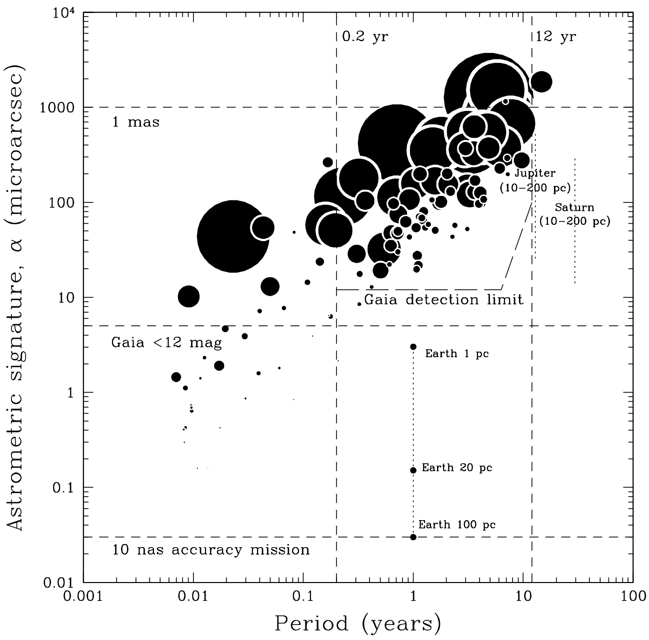


Figure 4: Astrometric signature, α, induced on the parent star for the known planetary systems, as a function of orbital period. Circles are shown with a radius proportional to $M_p \sin i$. Astrometry at the milli-arcsec level has negligible power in detecting these systems, while the situation changes dramatically for micro-arcsec measurements. Short-period systems to which radial velocity measurements are sensitive are difficult to detect astrometrically, while the longest period systems will be straightforward for micro-arcsec positional measurements. Effects of Earth, Jupiter, and Saturn are shown at the distances indicated.

Galactic bulge main-sequence stars. In about one case out of a million, sources in the bulge are lensed by foreground (bulge or disk) stars which are accompanied by the planets being sought. Observing high surface-density sky regions improves lensing probabilities to sufficient levels that successful detections can be expected over reasonable observing times. Space observations are considered mandatory to permit the high photometric accuracy required for detection even in very crowded regions where seeing limits the achievable photometric accuracy and hence detectability achievable from the ground.

Microlensing probes particular exo-planet domains: for example, low-mass planets can be detected, albeit usually at very large distances of typically 5–8 kpc. The sensitivity of such measurements is highest at (projected) orbital separations of 0.7–10 AU, but it will also detect systems with larger separations, masses as low as that of Mars, large moons of terrestrial planets, and some 50 000 giant planets via transits with orbital separations of up to 20 AU (the prime sensitivity of a transit survey extends inward from 1 AU, while the sensitivity of microlensing extends outwards). There are theoretical reasons to believe that free-floating planets may be abundant as a by-product of planetary formation, and MPF/GEST will also detect these.

The planetary lensing events have a typical duration of 2–20 hr (compared to the typical 2–20 weeks duration for lensing events due to stars), and must be sampled by photometry of $\sim 1\%$ accuracy several times per hour over a period of several days, and with high angular resolution because of the high density of bright main-sequence stars in the central bulge. The proposed polar orbit is oriented to keep the Galactic bulge in the continuous viewing zone. Most of the multiple-planet detections in the simulations of Bennett & Rhie (2002) are systems in which both 'Jupiter' and 'Saturn' planets are detected. Since multiple orbits are generally stable only if they are close to circular, a microlensing survey will be able to provide information on the abundance of giant planets with nearly circular orbits by measuring the frequency of double-planet detections and the ratios of their separations.

Just over 100 Earths would be detected if each lens star has one in a 1 AU orbit. The peak sensitivity is at an orbital distance of 2.5 AU, with 230 expected detections if each lens star had a planet in such an orbit. Although the prime quantity obtained from a microlensing detection is the mass ratio between planet and star, additional information or hypotheses can be combined to estimate the mass of the host star, the planetary mass, the distance to the host star, and the planet-star separation in the plane of the sky.

One of the disadvantages of lensing experiments is that a planet event, once observed, can never (in practice) be seen again – follow-up observations for further characterisations are not feasible (unlike the case for any of the other principal detection methods). Nevertheless, a mission like MPF/GEST will provide important observational and statistical data on the occurrence of low-mass planets (Earth to Jupiter masses), low-mass planets at larger orbital radii, multiple systems and, significantly, free-floating planets formed as a by-product of the system formation.

Detection by microlensing could in principle also be included in the Eddington mission, but the Eddington team has made no detailed evaluation of feasibility, and its inclusion would be likely to drive instrumental requirements in a non-trivial manner.

2.2.4 Other Space Missions: JWST, Spitzer, SOFIA

JWST: JWST (http://www.jwst.nasa.gov/) is a collaboration between NASA, ESA and the CSA. It will be a passively-cooled (40–50 K) observatory spacecraft with an 18-segment primary mirror having an effective aperture of about 6.5 m and diffraction-limited performance at $2\,\mu$m, equipped with four principal science instruments and a fine guidance sensor. It is scheduled for launch in 2011 into an L2 Lissajous orbit. The observatory is optimised for the $1–5\,\mu$m band, but will be equipped to cover $0.6–28\,\mu$m with a combination of imaging (through fixed and tunable filters) and low- to moderate-resolution ($100 < R < 3000$) spectroscopy. The 'Origin and Evolution of Planetary Systems' is one of JWST's five science themes, and the science requirements are drafted accordingly.

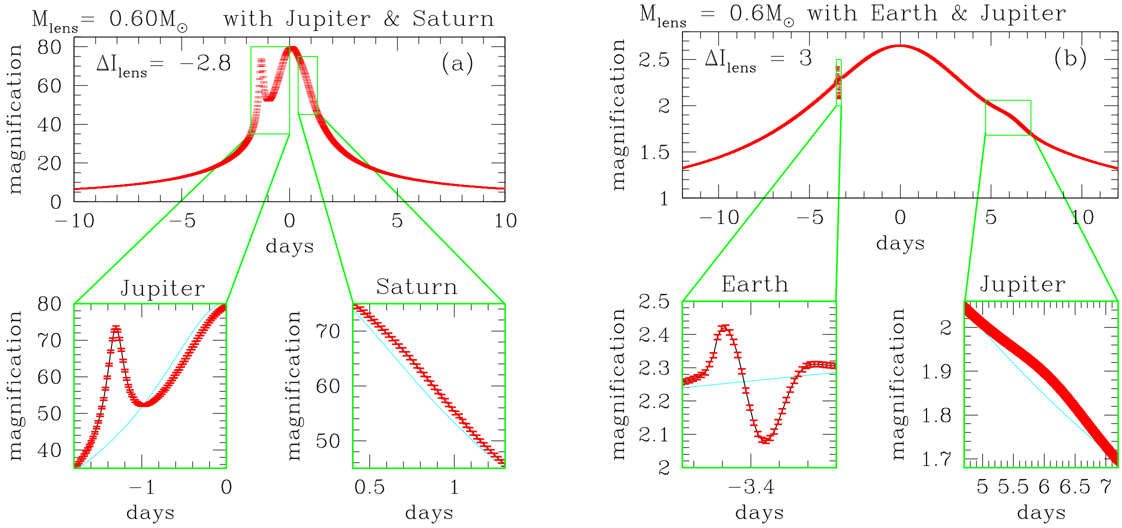


Figure 5: Example of multiple-planet microlensing light curves from the simulation of planetary systems with the same planetary mass ratios and separations as in our solar system, from the MPF/GEST studies of Bennett & Rhie (2002). Left: an example of a Jupiter/Saturn detection. Right: an example of the detection of an Earth and a Jupiter.

The Design Reference Mission (http://www.jwst.nasa.gov/ScienceGoals.htm) describes the exo-planet programmes currently foreseen for JWST. The survey programmes are aimed at finding giant planets and isolated objects using direct imaging, and bound planets using coronography. Follow-up studies are planned using tunable filter imaging ($R \sim 100$) and slit spectroscopy. For isolated sources, objects at AB = 30 mag can be reached using the near-infrared camera (NIRCam). The tunable filter can reach AB = 27 mag, while mid-infrared spectroscopy (with MIRI) can reach AB = 23 mag at $R \sim 3000$. For widely-separated giant planets, $R \sim 100$ coronography will provide preliminary temperature estimates and for these and for isolated systems, $R \sim 1000$ near-IR spectroscopy will access metallicity indicators. Synoptic observations of bodies in our own Solar System, such as Titan, over the 10-year lifetime of JWST will begin the study of secular surface and atmospheric changes.

A report on 'Astrobiology and JWST' (Seager & Lunine, 2004) listed three areas where the technical capabilities of JWST should be optimised for the follow-up of transit events: (1) in principle, JWST can measure the transmission spectra of giant planet atmospheres during planet transits of bright stars (7–14 mag) but this requires capabilities of rapid detector readout and high instrument duty-cycle in order to achieve very high S/N over a typical transit time (12 hr). If Earth-sized planets are common and detected in transit around stars brighter than 6 mag, the JWST near-IR spectrograph (NIRSpec) could detect atmospheric biomarker signatures; (2) the collection of $\sim 10^8$ photons per image for NIRSpec, by spreading photons over 10^5 spatial+spectral pixels, would enable JWST to characterise atmospheres during the transit of a terrestrial planet in the habitable-zone of a solar-type star; (3) NIRSpec is important for characterising transiting extra-solar planets. Many transiting extra-solar planets are expected to be found in the next several years with both ground-based and space-based telescopes (including Kepler). The short wavelength end is especially important for detecting scattered light and characterising planetary albedos. In particular, NIRSpec's long-slit configuration is essential for these observations. Thus JWST, even more so than HST, has considerable potential for follow-up observations of transiting systems discovered by other methods, for example by Kepler. This issue is developed further in Section 4.

Spitzer: Spitzer (ex-SIRTF, http://www.spitzer.caltech.edu/) is an 85 cm aperture, liquid helium cooled telescope in an Earth-trailing heliocentric orbit. Launched in August 2003, it has a projected lifetime (minimum) of 2.5 years with a goal of 5 years or more. The instrument complement provides the capabilities for imaging/photometry from 3–180 μm, spectroscopy from 5–40 μm and spectrophotometry from 50–100 μm. Spitzer's expected contribution to the field of exo-planet research lies in its ability to measure excess radiation from dust disks over the critical mid-infrared wavelength range. The imaging capability is determined by the diffraction limit of the relatively small telescope (1.5 arcsec at 6.5 μm). The sensitivity, however, allows the detection of dust masses to below the mass in small grains inferred in our Kuiper Belt (6×10^{22} gm) surrounding a Solar-type star at 30 pc.

One of the six Legacy Programs is concerned explicitly with the formation and evolution of planetary systems (see: 'The Formation and Evolution of Planetary Systems: Placing Our Solar System in Context' http://feps.as.arizona.edu/). This uses 350 hr of photometric and spectroscopic Spitzer time to detect and characterise the dust disk emission from two samples of solar-like stars, the first consisting of objects within 50 pc spanning an age range from 100–3000 Myr and the second containing objects between 15–180 pc spanning ages from 3–100 Myr.

The first call for Guest Observer programmes resulted in 8 accepted exo-planet proposals out of a total of 202 programmes in all subject areas. This includes one to characterise the atmosphere and evolution of the transiting extra-solar planet HD 209458b. The Cycle 2 call for proposals had a deadline of 12 Feb 2005. The accepted Guest Observer proposals related to exo-planets were:

* Ultracool Brown Dwarfs and Massive Planets Around Nearby White Dwarfs
* The SIM/TPF Sample: Comparative Planetology of Neighbouring Solar Systems
* Evolution of Gaseous Disks and Formation of Giant and Terrestrial Planets
* Searching the Stellar Graveyard for Planets and Brown Dwarfs with SST
* A Search for Planetary Systems around White Dwarf Merger Remnants
* Characterising the Atmosphere and Evolution of HD 209458b
* Survey for Planets and Exozodiacal Dust Around White Dwarfs
* Mineralogy, Grain Growth and Dust Settling in Brown Dwarf Disks

SOFIA: SOFIA (Stratospheric Observatory for Infrared Astronomy) is a joint endeavour of NASA and the German DLR (http://www.sofia.arc.nasa.gov/). A modified Boeing 747SP carrying a 2.7-m telescope will operate at an altitude of about 12 km. The first call for proposals will be issued in August 2005 for the first observing cycle starting in January 2006. A total of nine instrument have been selected, providing imaging and spectroscopy in the range 1–600 μm. Operating out of NASA Ames Research Center, the facility is to observe three or four nights a week for at least twenty years. Its location above the bulk of Earth's atmosphere will provide access to the mid-infrared region without the limitations of observatories on the ground. Its long projected lifetime will make it possible to conduct muli-epoch observations for variable or evolving objects and the ability to easily exchange instruments will ensure that the latest technology can be incorporated as it becomes available.

The science with SOFIA will revolve around cold matter in our solar system, the interstellar medium, stars and galaxies. Similar to Spitzer, SOFIA is not expected to contribute directly to the discovery of extra-solar planets, but it will enhance understanding of planet formation by studying circumstellar disks. Furthermore it will provide interesting information on the infrared spectra of solar system bodies including the chemistry of atmospheres.

2.3 Summary of Prospects 2005–2015

The prospects for the main search experiments described in this section are summarised in Table 5. This table presents only a simplified picture of planet detection capabilities, ignoring the comparative importance of finding large numbers of exoplanets with only an estimation of $M \sin i$ or r/R, or more comprehensively characterising a smaller number of planets (with mass, radius, albedo, and age). It also ignores the fact that different objects will be detected by different methods, and that different methods supply complementary astrophysical information.

Table 5: Predictions for the numbers of planet detections out to 2015 according to the major experiments currently planned, and the planet mass range given in the first column ($M_\oplus \sim 0.003 M_J$). The predictions depend sensitively on the (unknown) frequency of occurrence of (especially the lower-mass) planets, uncertain sample sizes, stellar jitter, etc. These are generally assessed somewhat differently for each project, and details are given in the accompanying text. The numbers must be understood as indications of possible developments only.

$M_{\rm Planet}$ (M_J)	2004 Radial Velocity (ground) (a)	2008–10 (b)	2008–10 Transits (ground) (c)	2008 COROT (d)	2010 Kepler (e)	2010–12 Eddington (f)	2015 SIM (g)	2016 Gaia astrom (h)	2016 photom (i)
1–10	90	200–250	100–1000	5–15	see below		200	15 000	3000
0.1–1	30	150–200	0	50–150	see below		50	5 000	0
0.01–0.1	0	10–20	0	10–30	see below		20	0	0
0.003–0.01	0	0	0	0–3	0–640	0–660	0–5	0	0

The columns of the table give results expected for: (a) the present situation, dominated by radial velocity detections; (b) the situation projected in the year 2010 from ground-based radial velocity observations (estimates by Udry, see Section 2.1.1); (c) ground-based transit detections: hot Jupiters extrapolated from Horne (2003); (d) COROT (estimates by Bouchy & Rauer, see Section 2.2.1); (e) Kepler (taken from the Kepler www site, see Section 2.2.1); (f) Eddington (estimates by Favata, see Section 2.2.1); (g) SIM (estimates by Perryman from the surveys noted in Section 2.2.2); (h–i) Gaia astrometric and photometric detections (see Section 2.2.2).

The estimated detections for Eddington are not available as a simple function of mass, but have been classified (as detailed under the relevant section) as follows, with the same assessment then made for the Kepler mission using the same assumptions:

– Eddington: 14 000 planets in total (in 12 500 systems)
– Kepler: 51 000 planets in total

– Eddington: 8000 hot planets, 5600 with $R > 5R_\oplus$
– Kepler: 30 000 hot planets, 22 000 with $R > 5R_\oplus$

– Eddington: 660 Earths ($0.5 < R < 2.0R_\oplus$)
– Kepler: 19 000 Earths ($0.5 < R < 2.0R_\oplus$)

– Eddington: 160 habitable zone planets, of which 20 'Earths'
– Kepler: 530 habitable zone planets, of which 35 'Earths'

While confidence is developing in statistical distributions of planets above about $0.05\,M_\mathrm{J}$, the occurrence of lower-mass, and specifically Earth-mass planets remains a matter for speculation. In this spirit, the lower range of detection limits for low-mass planets for Kepler, Eddington and SIM is indicated in the table as 0.

While these transit and astrometric discovery predictions must therefore be taken with certain caveats, they promise a major advance in the detection and knowledge of the statistical properties of a wide range of exo-planets: ranging from massive (Jupiter-mass) planets in long-period (Jupiter-type) orbits, and the occurrence and properties of multiple systems (via astrometry), through to Earth-mass planets in the habitable zone (via transits or microlensing).

3 The Period 2015–2025

3.1 Ground Observations: 2015–2025

3.1.1 OWL/ELT

The 100-m diameter Overwhelmingly Large Telescope (OWL) is being studied by ESO. S/N = 10 will be reached at 35 mag ($t = 1$ hr) for imaging, and at 30 mag for $R = 1000$ spectroscopy ($t = 3$ hr). The resolution, $\lambda/D \sim 1$ milli-arcsec in the V-band, is a factor 40 improvement over HST. Detection of Earth-mass exo-planets is part of the scientific case for the 100 m OWL/ELT project (see the on-line case for the European Large Telescope, ELT, at www-astro.physics.ox.ac.uk/∼imh/ELT, from which some of the following has been taken).

This section focuses on the science case and technical issues for Earth-mass planet detection. For this, OWL must be equipped with advanced adaptive optics systems to compensate for atmospheric seeing and the production of a near-diffraction limited image or image core, expected to deliver Strehl ratios S (the peak image brightness relative to that in a near-perfect image) from several to many tens of percent. In the near-infrared (1–5 μm), values near 90% may be attainable, and are needed for planet detection. Ultimate detection capabilities depend sensitively on whether such high Strehl ratios can be delivered in practice (such advanced AO systems do not yet exist). In addition, the telescope design (e.g. number and shape of elements) has an impact on the final image quality, even with co-phasing techniques, so that the exo-planet objectives must be considered early in the project.

Applied to a nearby solar-type star, adaptive optics produces an image with several components. A central 'spike' resembling a diffraction-limited image contains some S per cent of the total light, less a modest fraction diverted into the other, wider-spread components of the telescope point-spread function. The spike is surrounded by a residual halo containing the remaining light distributed like an unmodified seeing disc, i.e. with a generally Lorentzian distribution. This halo overlies, and within the seeing disk generally dominates, the fainter wings of the telescope point-spread function. These wings combine the light diffused by the small-scale imperfections of the optics and the accumulated dust, as well as the light diffracted by the central obstruction and geometric edges (mirrors, and supporting structures in the beam). The diffraction pattern is strongly dominated by the secondary mirror supporting structure, and by the edges of the mirror segments, which also produce strong secondary peaks.

The diffracted light can locally strongly dominate the uncorrected seeing light. The detailed structure of the halos in adaptive optics-corrected images is still being explored. At large radii they are composed of the rapidly varying diffraction-spot-sized 'classical' speckles. Less well-understood 'super-speckles' occur closer to the first 2–3 diffraction rings; larger, brighter, less rapidly variable and therefore less likely to average out on a long-exposure image. At the wavelengths of interest they should not, however, occur more than 10 milli-arcsec from the image centre, corresponding to 0.1 AU at a distance of 10 pc. Additionally, techniques such as simultaneous differential imaging may completely cancel these super-speckles. Nevertheless, their noise contribution remains even after subtraction, and is typically the strongest noise source in the 5–15 λ/D region. This can only be reduced by improving the Strehl ratio of the adaptive optics system.

Detection of a terrestrial-like planet in the presence of the stellar glare is made possible in principle by the relatively large angular separation between the image of a habitable planet and the central diffraction peak of its parent star. Thus at separations of 100 milli-arcsec (1 AU at 10 pc) only the sky background, the wider scattering components of the intrinsic point-spread function, and the adaptive optics halo contribute to the background. The orbital radius at which an exo-planet is in practice detectable is then bounded by two effects. At the inner extreme, the bright inner structures of the stellar image will drastically reduce sensitivity at angular separations below 10–20 milli-arcsec, corresponding to an orbital radius of 1 AU at 50 pc or 5 AU at 250 pc, so that beyond these distances only self-luminous exo-planets ('young Jupiters') could be detected. At the outer extremes, the brightness of the starlight reflected by the planet falls off with increasing orbital distance from the parent star, even though it is well separated from it. Some relevant scales are shown in Table 6.

Various techniques to increase the contrast of the images are at different stages of development, from theoretical concepts to working prototypes. The most promising are: (i) classic coronography, which involves masking the star in the focal and pupil planes; advanced Lyot stop studies taking into account the segmented mirror suggest that contrasts of 10^{-9} are achievable (neglecting diffusion by dust, mirror micro-roughness and the atmosphere); (ii) nulling interferometry (using the coherence of the star light to eliminate it interferometrically), (iii) extreme adaptive optics and multi-conjugated adaptive optics (which result in a higher Strehl ratio and cleaner point-spread function), (iv) simultaneous differential imaging (using the contrast of the target between nearby spectral bands and/or the polarisation of the target). Some of these methods can be combined to reach yet higher contrast (Codona & Angel, 2004).

The wavelength range where a broad range of planets may best be detected and studied with OWL is probably the near infrared J-band at 1.25 μm (where achievable Strehl ratios should approach 90% and where strong spectral features of water are available as diagnostics), and the far red Z and I bands extending down to 700 nm (less favourable for adaptive optics, but containing the critical O_2 B-band absorption complex at 760 nm). In the centres of the stronger absorption bands saturated lines will obscure the signal from an exo-Earth. However, in the wings numerous narrow unsaturated but detectable lines will move in and out of coincidence as the two planets move around their respective suns with a modulated Doppler shift of up to 50 km s^{-1}. As discussed in Section 1.2, free oxygen in the exo-planet atmosphere

Table 6: Magnitudes and separations for exo-planets predicted for OWL (estimated by Hainaut). Separations are given in arcsec. Contrast ratios between the planets and the parent star are of order 10^{-8} to 10^{-9}. The magnitudes of the planets were taken as follows: Jupiter: real observations; Earth: real observations of the Earth, and for some wavelength where no observations were available, constructed by scaling observations of Venus and/or Mars; hot Jupiter: models by Sudarsky et al. (2003) and Burrows et al. (2004), for a planet with $M = 1 M_J$ and $a = 0.2$ AU.

Distance (pc)	Star (mag)	Hot Jupiter 0.2 AU	Earth 1 AU	Jupiter 5 AU
10	4.8	V = 24.1	27.9	25.8
		sep = 0.020	0.100	0.500
25	6.8	V = 26.1	29.9	27.8
		sep = 0.008	0.040	0.200
50	8.3	V = 27.6	31.4	29.3
		sep = 0.004	0.020	0.100
100	9.8	V = 29.1	32.9	30.8
		sep = 0.002	0.010	0.050

would be a strong indicator of life (i.e. of photosynthetic biochemistry), while its absence would not be conclusive evidence for an abiotic world.

Table 8 indicates the S/N that can be expected from a 24 hr OWL observation of an Earth at 10 pc, in the optical and near-infrared. Clearly, even if Earths exist at distances as close as only 10 pc, detection and spectroscopy will be challenging even with OWL. Concerning the number of target stars accessible for investigation by OWL, the Darwin study identifies some 500 F5–K9 stars out to 25 pc, of which some 285 are single. There are only some 2–5 G0V–G2V stars within 10 pc, and some 21 single, non-variable G0V–G4V within 15 pc.

The distance at which an Earth will be observable will depend on various parameters (Strehl ratio achievable, the performance of nulling/subtraction techniques, e.g. phase-induced apodization coronography could yield attenuation of 10^{-9}, etc.) but in any case is a strong function of mirror diameter. Assuming, as above, that a telescope can see a planet beyond an angular distance of $5\lambda/D$ from the parent star, the volume of space explored (i.e. the number of stars) is proportional to D^3, and the numbers for G stars go from about 25 for a 30 m telescope to about 900 for a 100 m. The time to achieve the same S/N for different size telescopes scales as $(\mathrm{S/N})^{-2}$; the object lies within the uncorrected light from the star, so measurements are in the background-limited regime, i.e. $S \propto D^2$, background $\propto D^2$, pixel size $\propto D^{-2}$ (being diffraction limited) so $\mathrm{S/N} \propto D^2/\sqrt{D^2 \times D^{-2}} = D^2$ and $t \propto D^{-4}$. Thus a 30 m aperture would take 123 times longer than a 100 m to observe an object that both would separate from the parent star. This is also the reason why a lower limit of about 70 m diameter is considered useful for spectroscopy of the very nearest exo-solar systems, and why 30 m telescopes do not include Earth-like exo-planets as part of their scientific goals.

Table 7: Distance limits and numbers of stars searchable by ELT/OWL as a function of planetary mass and primary mirror diameter (estimated by Hainaut). The detailed assumptions (noise sources, exposure times, etc.) have not been documented, and these results should be taken as indicative and preliminary. They also rest on the feasibility of achieving the high Strehl ratios referred to in the text.

D(m)		Earth-mass		Jupiter-mass	
		Imaging	Spectroscopy	Imaging	Spectroscopy
30	d(pc)	10	–	70	5
	n(star)	22	0	6800	3
60	d(pc)	22	–	120	18
	n(star)	210	0	35 000	170
100	d(pc)	40	15	500	35
	n(star)	1200	67	2 500 000	860

The limiting distances at which imaging and spectroscopic observations can be performed must take into account the photon noise from the star, sky and planet, the speckle noise for a realistically high Strehl ratio, and slowly varying aberrations that contaminate the image subtraction. From these distances, the number of host candidates are obtained from star catalogues (e.g., keeping only single G and early K stars). Results are shown in Table 7. The actual number of planets which will be discovered is a function of the (unknown) fraction of planets per star. The conclusions of the OWL studies are that the number of stars accessible to a 100 m telescope is large enough to secure spectroscopic measurements of a large number of planets. In the case of spectroscopy of Earths at 1 AU, however, the number of accessible stars is just large enough to guarantee that a few planets should be observable. These observations will be difficult (but hopefully feasible) for a 100 m telescope, but are out of reach of smaller telescopes. These preliminary conclusions clearly all require further evaluation.

After the mechanical assembly of the OWL telescope is completed, the mirror cell will start to be populated with segments. It is expected that that phase will take a few years (~ 3), during which the telescope will already be available for scientific observations, although with a reduced collecting area. The configuration of the segments in the cell during this filling phase is still under discussion, but an attractive option is to place them in such way that OWL could be used as a 'hyper-telescope', i.e. an interferometer with densified pupil, assuming that proper phasing can be achieved in such a scheme. In such configuration, the resolution and imaging characteristics are very similar to that of a filled aperture telescope with the full diameter (cf. Riaud et al. (2002) and Appendix B), but with a very small accessible field (of the order of λ/d of a single segment), i.e. ~ 0.1 arcsec, which is very suitable for a planet detection. Science time during the mirror assembly phase could then be used to perform a broad survey for planets around nearby stars. Assuming 100 nights of observations per year for 2–3 years, 1 hr per single observation, and 8–10 epochs per star in order to sample the (potential) planet orbit, of the order of 300 stars could be searched for planets. In that way, a catalogue of targets would be made available for further studies. While the detection limit would not be as deep as that of the full, completed OWL, objects discovered with the early, hypertelescope version would have characteristics (separation and intrinsic magnitude) that would permit further physical studies with the completed telescope.

In conclusion, it is stressed that there remain technical uncertainties in inferring that OWL can indeed observe Earth-type planets: the major assumptions which must be clarified over the coming years are that adaptive optics can work as needed, producing the required Strehl ratios, and providing adequate S/N ratios in both continuum and spectral diagnostic lines. Tracking is not seen as a comparable issue: if the telescope can track to sub-arcsec accuracy (it does according to analysis, at some 0.3 arcsec rms with $10\,\mathrm{m\,s^{-1}}$ wind and taking into account friction in drives, and without field stabilisation with M6), then the problem of pointing stability is a control loop issue comparable to adaptive optics but with a much lower frequency.

Even though smaller ELTs, such as the 30-m TMT (Thirty-Metre Telescope), will not reach Earth-like planets, there is still a scientific niche for them between the objectives of VLT-Planet Finder and OWL: notably, detection and characterisation of giant planets, of all ages, and close to their parents stars. Evidently, their technical challenges will be easier to reach than those for a 100-m aperture.

The astrometric capabilities of OWL remain to be assessed, but narrow-angle astrometric prospects should be very good, and provision of an astrometric facility in the instrument plan may be appropriate.

3.1.2 Observations at an Antarctic Site

Excellent ground-based astronomical sites in terms of telescope sensitivity at infrared and submillimeter wavelengths are located on the Antarctic Plateau, where high atmospheric transparency and low sky emission result from the extremely cold and dry air; these benefits are well characterised at the South Pole station. The relative advantages offered by three potentially superior sites, Dome C, Dome F, and Dome A, located higher on the Antarctic Plateau, are quantified by Lawrence (2004). In the near- to mid-infrared, sensitivity gains relative to the South Pole of up to a factor of 10 are predicted at Dome A, and a factor of 2 for Dome C. In the mid- to far-infrared, sensitivity gains relative to the South Pole up to a factor of 100 are predicted for Dome A and 10 for Dome C. These values correspond to even larger gains (up to 3 orders of magnitude) compared to the best mid-latitude sites, such as Mauna Kea and the Chajnantor Plateau.

Thus these Antarctic sites appear to offer extremely good conditions for future interferometric projects and for (robotic) photometric surveys, yielding one long observing ‘night’ per year (completely dark in June–July, decreasing to 7 hr darkness during March and October, although with an extended 'twilight' period due to the fact that the Sun does not set very far below the horizon). Table 8 shows that an Antarctic OWL might achieve comparable performances to Darwin/TPF in the near-infrared; currently this is viewed as somewhat hypothetical, given the complex logistics and formidable meteorological conditions for construction and operation.

Dome C (elevation 3250 m, latitude $-75°$) is the site of the French-Italian Concordia station, whose main characteristics have been studied over the last few years. It provides: (i) an ambient temperature ranging from 195 K (winter) to 235 K (summer), resulting in low, stable thermal emission; (ii) extremely dry air (250 μm precipitable water vapour typical), resulting in enlarged and improved infrared transmission windows; (iii) very low surface winds (median wind speed of $2.7\,\mathrm{m\,s^{-1}}$, and below $5\,\mathrm{m\,s^{-1}}$ for more than 90% of the time), resulting in very low free-air turbulence, with a quasi-absence of jet streams since Dome C is located inside the polar vortex; (iv) some 80% of clear skies. The combination of coldness and dryness for the atmosphere results in infrared photometric gains that peak at about a factor of 25 in the K and L bands, i.e. an Antarctic 1.8-m telescope is more efficient than an 8-m telescope at a temperate site. In the H and N bands the gain (of order 3) is also notable although less dramatic.

Exceptional winter conditions were confirmed by teams from the University of Nice (Aristidi et al., 2003) and Australia UNSW (Lawrence et al., 2004): over a 3-month period, the median seeing was 0.27 arcsec, with 0.15 arcsec achieved for more than 25% of the time. As most of the turbulence is located near the ground, the isoplanatic angle is enlarged (5.9 arcsec under normalised conditions, compared with 2.9 arcsec for Paranal) which improves the field of view (and the likelihood of finding a reference star) for adaptive optics. This has consequences in the feasibility of adaptive optics for ELTs, where multiconjugate systems and laser guide stars may no longer be needed. Because the turbulence is generated by low-velocity winds, it is slow, meaning better sensitivity and improved phase correction for adaptive optics systems. There is still some debate about the normalised coherence time (whose median value is 2.6 ms on Paranal): indirect measurements with the MASS scintillometer indicate a median value of 5.9 ms, while direct DIMM measurements show a correlation of the image motions beyond 250 ms (as expected from $r_0 = 50$ cm and a typical $2.5\,\mathrm{m\,s^{-1}}$ wind speed).

Even taking the most pessimistic value (5.9 ms), the coherence volume that drives the sensitivity of adaptive optics and interferometric systems is improved by a typical factor of 20, if the AO wavefront sensor operates in the K-band. When combined with the factor of 25 photometric gain, this results in an expected sensitivity for interferometers and AO systems 500 times better than a similarly equipped temperate site. For bright sources, higher dynamic range observations (either by coronography or nulling) can be achieved due to the reduced phase and background noise.

Current adaptive optics mainly concerns the correction of the phase of the wavefront to achieve diffraction-limited imaging. Even after a perfectly plane wavefront has been produced, diffraction effects caused by scintillation may dominate in the far wings and halos of the image. Scintillation, originating in inhomogeneities of the higher atmosphere, causes patterns of ‘flying shadows’ on the ground (with intensity contrasts of perhaps only a few percent), carried across the telescope pupil at the windspeed of the originating atmospheric layer. In principle, this could be corrected by second-order adaptive optics (modulating both the phase and amplitude), but the task is not trivial. An additional advantage for Dome C (assuming that ‘ordinary’ adaptive optics will be fully operational) is that such sites also appear to have very much less scintillation: not only do the low windspeeds (no jet streams such as prevail over Chile and Hawaii) imply much less energy deposited in atmospheric turbulence, but the winter-time atmospheric structure is such that the tropopause effectively reaches the ground, with no significant temperature discontinuities in the higher atmosphere.

In the most favourable cases (K band and an L band extended to 2.8–4.2 μm) Dome C thus provides a near space-quality environment, presumably at a small fraction of the cost, and with almost no limitations in weight or volume. The logistics for the station were developed by the French (IPEV) and Italian (PNRA) polar institutes: humans reach the site by plane with a total travel time of about 48 hr from Europe, while the heavy equipment is shipped in standard containers by boat to the coast and then by pack trains of Caterpillar trucks onto the glacier slopes up to Concordia.

It is still the accepted wisdom that a census of exo-Earths and the characterisation of their atmosphere (in search for biomarkers) will require a space mission such as Darwin. The survey part of the Darwin programme could perhaps be undertaken from Dome C, given the extreme phase and background stability of the site. A preliminary study should be undertaken to determine whether this could be achieved, either with a coronographic ELT in the visible or near-IR, or a large interferometer in the thermal infrared. This would enable Darwin to concentrate on the spectroscopy of identified targets, i.e. at wavelengths 6–18 μm where clear biomarkers exist and which for the most part are not accessible from Dome C. A simplified interferometer (two 1 m telescopes) equipped with a GENIE-type instrument could provide good-quality spectra of hot (Jupiter- or Neptune-class) bodies and the characterisation of exo-zodiacal light around main-sequence nearby stars – precursor science for Darwin that otherwise necessitates extensive use of VLT UT time. Other applications of Dome C for exo-planets include astrometry and transit photometry. The ultimate astrometric accuracy of an interferometer was estimated by Swain et al. (2003) to be a factor of some 30 better at Dome C than at Paranal. However, before this potential gain is realised, the technique must have matured to the point where astrometry on temperate sites is limited by the atmosphere only, and not by systematic effects. Transit photometry could benefit from lower scintillation, and longer continuous time coverage (polar night), than on temperate sites.

The nature of the site, halfway between ground and space, makes it an especially interesting area for collaboration between ESO and ESA. Although Europe is naturally in a leadership position due to the presence of the Concordia station, Dome C operation is made in a fully international (Antarctica Treaty), politically interesting ('continent of science') context, which may help to gather resources and foster international cooperation (Australia, USA, China) for a large project. A major facility could be proposed at the EU level in 2007, as part of the FP7 programme, and in coincidence with the International Polar Year.

While an interferometer along the lines of GENIE seems very appealing, building OWL at Dome C is a different matter. Exo-planet studies are going to be one of several science drivers for any ELT. Limited sky coverage, and logistics, may be the limiting factors.

Meanwhile, specific concepts being studied include:

(a) a 0.8-m Italian project, featuring a mid-infrared imager (5–25 μm) and possibly a 1–2.5 μm spectrograph. Construction at Dome C has started, and first light is scheduled for December 2005;

(b) a large Australian Dome C development proposal including various groups involved in a 2-m optical/IR telescope (PILOT). Associated structures at Dome C are already advancing, with the first winter-over starting in 2005;

(c) a robotic reflective Schmidt telescope for Dome C by Strassmeier et al. (2004);

(d) a successful bid for NSF study money for Phase 1 of an Antarctic Planetary Interferometer (API), to be placed at Dome C (PI: Mark Swain). Phase 1 is intended to be capable of atmospheric spectroscopy of gas giants, whereas it will take a full Phase 2 system to target Earth-like planets;

(e) a French concept for a Dome C interferometer called KEOPS (Kiloparsec Explorer for Optical Planet Search, PI: Farrokh Vakili). Proposed timescales cover the current study phase (telescopes, beam stabilisation, co-phasing, delay lines, recombiner, coronograph); a single 1.5-m telescope operation in 2007; a simple interferometer with 2 telescopes in 2008–09; first 6-telescope ring system, possibly in association with API, around 2015; and a full 36-telescope system in the more distant future.

3.2 Space Observations: 2015–2025

The literature makes no reference to transit missions beyond Kepler and Eddington, nor astrometric missions beyond SIM and Gaia, all due for completion around 2015. Rather, space missions projected for 2015–20 and beyond fall into the category of 'imaging' or 'direct detection' concepts, notably Darwin and/or TPF. 'Imaging' here generally refers to imaging of the exo-planetary system, i.e. direct detection of the exo-planet as a point source of light distinct from that of the parent star, and *not* to resolved imaging of the exo-planet surface.

The next major break-through in exo-planetary science will be the detection and detailed characterisation of Earth-like planets in habitable zones. The prime goals would be to detect light from Earth-like planets and to perform low-resolution spectroscopy of their atmospheres in order to characterise their physical and chemical properties. The target samples would include about 200 stars in the Solar neighbourhood. Follow-up spectroscopy covering the molecular bands of CO_2, H_2O, O_3, and CH_4 will deepen understanding of Earth-like planets in general, and may lead to the identification of unique biomarkers. The search for life on other planets will enable us to place life as it exists today on Earth in the context of planetary and biological evolution and survival.

In the more distant future, perhaps well beyond 2025, a successful Darwin/TPF would logically be followed by 'life finders' and true 'planet imagers'. At present they appear only as more distant goals, and a brief discussion of them is given in Appendix B. They are unlikely to affect ESA/NASA policy over the next decade or more, at least until the prospects for the success of Darwin/TPF can be quantified, except in the areas of advanced technology studies. Similarly, ideas beyond Darwin/TPF are unlikely to influence the choices or prospects for the very large (50–100 m) telescopes on ground.

3.2.1 Darwin

Darwin is the ESA mission concept aiming at the direct detection of exo-planets, and is focused on an interferometer configuration. It was originally conceived as a set of eight spacecraft at L2 (6 telescopes, one beam combination unit, and one communication unit) that would survey 100 of the closest stars in the infrared, searching for Earth-like planets and analysing their atmospheres for the chemical signature of life (Fridlund, 2000), scientific objectives in common with those of TPF. More recent studies have identified a simplified option, employing 4 telescopes separated by up to 50–100 m operated in a 'dual-Bracewell' configuration (or possibly 3×3.5 m telescopes), requiring a dual Soyuz-Fregat launch, and a target launch date of 2015. The mission foresees a detection phase of 2 years (allowing the follow-up of 150–200 stars), and a spectroscopy phase of 3 years. Specific precursor efforts include a possible space mission (Smart-3) to demonstrate the concept of forma-

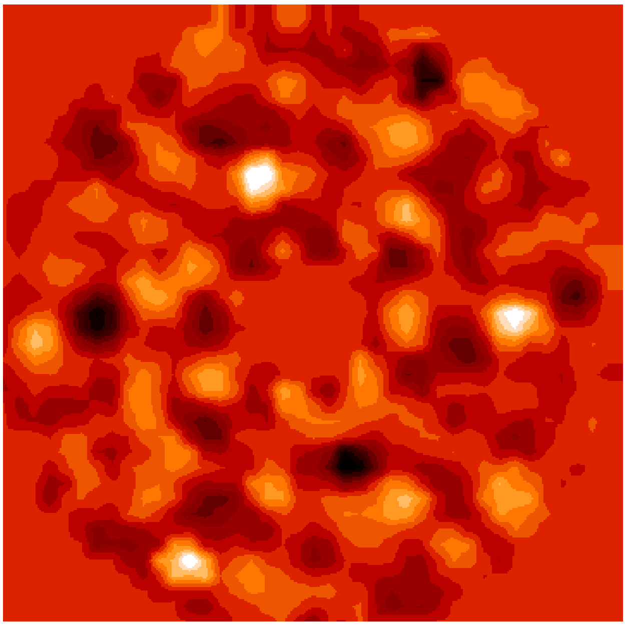


Figure 6: A 2×2 arcsec^2 simulated image of our Solar System viewed from 10 pc using the (former) 6-telescope Darwin configuration. Observations are over 6–18 μm in a 10-hour exposure, with the system viewed at 30° inclination, and assuming zodiacal emission as for our Solar System. The Sun is located at the centre. Venus, Earth and Mars are visible.

tion flying. The emphasis on the infrared rather than the optical is guided by: (i) the less-stringent requirements on technology (contrast and resolution); (ii) infrared spectroscopy allows characterisation in a direct and unambiguous manner; (iii) infrared interferometry allows a larger sample of objects to be surveyed for Earth-like planets (150–200 versus 32 for visual coronography); (iv) it provides the heritage for the next generation of missions which will demand higher resolution spatial imaging. Figure 6 is a simulated image of our Solar System viewed from 10 pc.

Table 8, from Angel (2003), is a summary of detection capabilities for an Earth-Sun system at 10 pc for various experiments being studied, including TPF and Darwin. It shows that even for the most ambitious projects being planned at present, direct detection of even a nearby Earth represents a huge challenge.

Table 9 summarises the estimated integration times for a variety of stellar types (target stellar types are F–G with some K–M), and a range of distances. Broadly, these are consistent with the simplified summary given in Table 8. Typical distance limits are out to 25 pc. A terrestrial planet is considered as $R_{\rm max} \sim 2R_\oplus$. The spectral range is 6–18 μm, covering the key absorption lines, with a spectral resolution of 20 (50 is required for CH_4 in low abundance). Integration time estimates are given for a S/N = 5 in imaging (i.e. detected planetary signal/total noise) and S/N = 7 in the faintest part of spectrum for spectroscopy, for the following assumptions: total collecting area for all telescopes of 40 m^2; telescopes at 40 K; effective planetary temperature 265 K (signal scales as $T_{\rm eff}^4$); $R = R_\oplus$; integrated over 8–16

Table 8: Detection capabilities: Earth at 10 pc, from Angel (2003). $\Delta\theta = 0.1$ arcsec, $t_{\rm int} = 24$ hr, QE = 0.2, $\Delta\lambda/\lambda = 0.2$. Mode = N corresponds to a nulling system, C to a coronograph. The ground-based results assume that long-term averaging is realistic, with fast atmospheric correction. For further details of assumptions, see Angel (2003)

Telescope	Size (m)	λ(μm)	Mode	S/N	Comment
Darwin/TPF-I	4×2	11	N	8	See also Table 9
TPF-C	3.5	0.5	C	11	Typical launcher diameter
"	7	0.8	C	5–34	
Antarctic	21	11	N	0.5	
"		0.8	C	6	
CELT, GMT	30	11	N	0.3	30 m [C] too small at 11 μm
"		0.8	C	4	
OWL	100	11	C	4	Large Φ [C] for IR suppression
"		0.8	C	46	Optical spectroscopy possible
Antarctic OWL	100	11	C	17	Comparable to Darwin/TPF, but O_3 (9.6 μm) and CO_2 (15 μm) not accessible (atmosphere opaque)
"		0.8	C	90	Water bands at 1.1–1.4 μm

μm; 10 times the level of zodiacal dust than in the inner solar system; all of the habitable zone is searched; Spitzer Si-As detectors. Times given are based on a 90% confidence level for a non-detection based on 3 observations (a positive detection at S/N = 5 then takes one third of the times given). To detect the Earth at 265 K (instead of 290 K) around the Sun at 20 pc would take 9 hr at S/N = 5, and 36 hr at S/N = 10. For a K5V star at 10 pc these times are about 1–4 hr respectively. For spectroscopy, the S/N varies between 7 and significantly higher, depending on the atmosphere. For an Earth atmosphere (but at 265 K) at 20 pc, an integration time of 54 hr provides a S/N$\sim 7-15$.

One of the strongest noise sources is the leakage of photons from the resolved stellar surface. This is a function of both stellar temperature and diameter (distance, spectral type). It is most clearly seen for nearby stars where the detection time drops strongly. For 20 pc detection times do not change much since the star does not leak very much for any diameter. Detection times rise rapidly for K5V stars at 30 pc, because of the 90% confidence requirement, which itself demands more changes in array size because the habitable zone is very close to the star.

The number of candidates accessible and visible to Darwin (two $\pm45^\circ$ caps near the ecliptic poles are inaccessible) is estimated as follows. Considering only single stars, there are 211 K and 82 G candidates out to 25 pc, with another 30 F-type stars plus many M-dwarfs. Combined with the integration time estimates, Darwin should survey more than 150 stars in 2 years. Within 5 years, all 293 single and accessible solar-type stars stars out to 25 pc can be surveyed, with a spectrum obtained for each system in the case of a planet prevalence of $\sim$10%. Up to 1000 systems in the solar neighbourhood could be surveyed if the planetary fraction is even smaller.

3.2.2 The Darwin Ground-Based Precursor: GENIE

GENIE is a nulling interferometer under development by ESA and ESO for the VLTI. GENIE will allow the development and demonstration of the technology required for nulling interferometry, allowing testing of the Darwin technology in an integrated and operational system (amplitude control loops, high-accuracy optical path difference control loop, dispersion control, polarisation compensation, background subtraction, and internal modulation). GENIE is considered by the Darwin project as necessary for demonstrating these technical concepts in advance of launch.

Two competitive instrument definition studies were due for completion by the end of 2004, with the scientific case being prepared in collaboration between ESO and ESA. GENIE will be considered by the ESO Council in April 2005, and could be operational by mid-2008. If not accepted by ESO, a separate laboratory technology demonstrator would be needed to validate the Darwin concepts.

GENIE is also considered mandatory as a specific instrumental configuration to survey southern-hemisphere target candidates, in order to decide which targets are most suitable for observation by Darwin, and specifically to characterise the level of exo-zodiacal light, which must be below certain limits necessary for exo-planetary detections. A corresponding programme is planned to be undertaken at the Keck telescope in the northern hemisphere for preparations for TPF. Studies by den Hartog et al. (2004) show that the capabilities of GENIE are sufficient to detect the planet around τ Boo within 1 hour, and by inference some 5 other candidate 'hot Jupiter' planets. GENIE could use either the VLT UTs or ATs, at a wavelength of $3.6\,\mu$m, and will require a significant number of observing nights (of order 50).

The main limiting factors for GENIE are the phase and thermal background stability on Paranal, as well as system complexity issues involved with its integration into the existing VLTI environment. If GENIE were located on the high Antarctic plateau (Dome C) where the thermal background is lower, and the seeing both better and slower (see Section 3.1.2), the performance required to perform its science programme could perhaps be achieved using smaller (of order 1 m) telescopes and a simpler, dedicated system architecture. This has to be balanced against the reduced sky coverage at $-75°$ latitude, and probably more complex logistics.

Table 9: Darwin: integration times for detection of Earth-like planets at S/N = 5, and spectroscopy at S/N = 7 in the faintest part of the spectrum (in hours). See text for details.

Stellar type	10 pc	20 pc	30 pc
G2V	18–33	28–54	109–173
G5V	12–22	27–46	105–166
K2V	4–9	26–37	104–157
K5V	4–6	26–35	249–155

3.2.3 Terrestrial Planet Finder (TPF)

NASA's TPF roughly parallels the ESA Darwin study, with close discussions taking place between the two teams. TPF was conceived to take the form of either a coronograph operating at visible wavelengths or a large-baseline interferometer operating in the infrared (Beichman, 2003). There are two aspects of this choice which should be distinguished: (a) the scientific aspect: whether reflected (visible and near IR) light or thermal emission (mid-IR) is the best regime to characterise planets (albedo, temperature, colour, key species that can be identified e.g. CO_2 etc.; see Schneider (2003) for a recent discussion); (b) the instrumental aspects: whether an interferometer or a coronograph is the best. Here, the NASA Technology Plan for TPF stated that 'Technology readiness, rather than a scientific preference for any wavelength region, will probably be the determining factor in the selection of a final architecture'. In May 2002, two architectural concepts were selected for further evaluation: an infrared interferometer (multiple small telescopes on a fixed structure or on separated spacecraft flying in precision formation and utilising nulling), and a visible light coronograph (utilising a large optical telescope, with a mirror three to four times bigger and at least 10 times more precise in wave-front error than the Hubble Space Telescope).

In April 2004, NASA announced that it would embark on a 6×3.5 m^2 (more recently changed to 8×3.5 m^2) visual coronograph in 2014 (TPF-C), with a wavelength range 0.6–1.06 μm, and targeting a full search of 32 nearby stars and an incomplete search for 130 stars (more recently quoted as 80). A free-flying interferometer, in collaboration with ESA, would be considered before 2020 (TPF-I).

A visible light system can be smaller (some 10 m aperture) than a comparable infrared interferometer, however advances in mirror technology are required: mirrors must be ultra-smooth ($\sim \lambda/15\,000$; a number stated in the TPF documentation, although values an order of magnitude inferior appear more plausible) to minimise scattered light, and in addition active optics would be needed to maintain low and mid-spatial frequency mirror structure at acceptable levels. Infrared interferometry would require either large boom technology or formation flying, typically with separation accuracies at the cm-level with short internal delay lines. For the detection of ozone at distances of 15 pc and S/N$\sim$25, apertures of about 40 m^2, and observing times of 2–8 weeks per object, are indicated.

Many ideas for scientific and technological precursors for TPF have been examined. The many possible solutions involve combinations of adaptive wavefront correction, coronographs, apodization, interferometers, and large free-flying occulters. The main contenders are summarised in Appendix A for completeness, although with the recent (April 2004) NASA announcement on TPF strategy, it is not clear whether any of these concepts will be developed further.

3.3 ESA Themes: 2015–2025

In mid-2004, ESA solicited a call for ideas for its scientific programme beyond 2015, resulting in several outline proposals in the area of exo-planets:

A Large UV Telescope (Lecavelier): the proposal considers a large UV telescope as a promising way to conduct a deep search for bio-markers in Earth-mass exo-planets, through the detection of relevant atmospheric signatures (such as ozone, water, CO, and CO_2) in a very large number of exo-planets, and planetary satellites, up to several hundred parsec distant. It notes that the detection of atmospheric signatures in HD 209458b has been made through space UV observations, and stresses that large numbers of prime targets for these observations will be detected by Gaia. It underlines the possibility of time-resolved spectroscopy (over the 10-min typical transit time of an Earth-mass planet) providing spatial information of atmospheric constituents along the planet surface (poles versus equator, presence of continents). A JWST-size telescope is proposed, and some quantitative expectations are given.

Search for Planets and Life in the Universe (Léger): the proposal makes the general case for the continued development of an ESA strategy for the improved detection and characterisation of exo-planets, primarily through the techniques of transits and direct detection. This proposal was submitted on behalf of more than 200 individuals and institutions.

Astrometric detection of Earth-Mass Planets (Perryman): the proposal points out that, beyond the micro-arcsec astrometric accuracies of ESA's Gaia mission, 10 nano-arcsec accuracies would permit the detection of astrometric perturbations due to Earth-mass planets around Sun-like stars at 100 pc. If a survey-type mission were feasible, the concept could lead to the systematic survey of many hundreds of thousands of stars for Earth-mass planets – important for the generation of target objects if the fraction of Earth-mass planets turns out to be very small. Earth-mass perturbations around a solar-mass star are 300 nano-arcsec at 10 pc, or 30 nano-arcsec at 100 pc, the latter requiring an instantaneous measurement accuracy a factor 3 better, i.e. 10 nano-arcsec at, say, 12 mag. This is a factor of some 1000 improvement with respect to Gaia. Keeping all other mission parameters (efficiency, transverse field of view, mission duration, total observing time per star, and image pixel sampling, etc.) unchanged, we can consider reaching this accuracy simply through a scaling up of the primary mirror size. The Gaia primary mirror has an along-scan dimension $D = 1.4$ m and a transverse dimension $H = 0.5$ m; the final accuracy scales as $\sigma \propto D^{-3/2}H^{-1/2}$. These desired accuracies would therefore require a primary mirror size of order 50×12 m^2, and a focal length (scaling with D) of about 1600 m, similar to the scale of the optics derived for the mini-version of Life Finder. Accuracy levels of $\sim$ 10 nano-arcsec are still above the noise floors due to interplanetary and interstellar scintillation in the optical, or stochastic gravitational wave noise. Astrometric accuracy limits due to surface granular structure and star spots were discussed in Section 1.3. To reach the astrometric precision of 300 nano-arcsec at 10 pc means that the photocentre of a star must be determined to

$\sim 5 \times 10^5$ m, or $1.5 \times 10^{-4}\, R_\odot$. This is still significantly above the photometric stability limits of $10^{-7} - 10^{-8}$ AU, or $10^3 - 10^4$ m, derived by Svensson & Ludwig (2005) for stars with $\log g = 4.4$. Note, however, that this only concerns thermally-driven granulation, thus determining only the lowest possible level of stellar astrometric stability.

Understanding the Planetary Population of our Galaxy (Piotto): the proposal underlines the importance of the field to ESA and to Europe. It argues that most disciplines start with the discovery and study of individual objects, before moving on to the more mature stage in which large, unbiased samples of objects are studied. In the decade 2015–25, an open issue will be the discovery and characterisation of large unbiased samples of planets down to habitable systems. This should provide information necessary to understand how the environment and nature of the parent star affects the resulting planetary population; how stellar metallicity, multiplicity, crowding, and population influence the nature, habitability and survival of planetary systems. The proposal suggests a transit-type follow-up to Kepler/Eddington, using a significantly larger aperture and improved detector technologies to obtain much improved samples/statistics; combined with the availability of large (> 25 m) ground-based telescopes for follow-up spectroscopic observations.

Exo-planet Detection and Characterisation (Surdej): the proposal underlines the general importance of the field to ESA and to Europe, and proposes to intensify efforts towards a Darwin-like mission, including further emphasis on coronography, perhaps as an ESA instrument on TPF-C. The proposal also underlines the importance to astrobiology of sample-return missions in the Solar System, for example to Mars, Europa, and Titan. Otherwise, no specific instrument approach or design is considered.

Evolution of Atmospheres and Ionospheres of Planets and Exo-Planets (André): the proposal considers a combination of *in situ* observations of Solar System planets and remote sensing of exo-planets in order to advance understanding of the long-term evolution of the atmospheres and ionospheres of planets (and large moons), and to identify the important sources and sinks of atmospheres and ionospheres of planets during different parts of their evolution. No specific instrument approach or design is considered.

Planetary Habitability in the Solar System and Beyond (Bertaux): the proposal underlines the general importance of the field to ESA and to Europe. It includes suggestions for intensifying the search for (past) life on Mars through robotic exploration in order to refine probability estimates of life beyond the Solar System. It also notes the potential problem that ESA's Darwin mission is presently designed as its own candidate surveyor, and argues that a preliminary programme, possibly ground-based, should undertake the advanced search so that Darwin can focus its observing time on spectral acquisition of Earth-mass planets. The suggestion is to conduct this survey, under ESA responsibility, using Doppler measurements, reaching the required accuracies of 0.1–0.8 $\mathrm{m\,s^{-1}}$ through the accumulation of large number of individual 1–2 $\mathrm{m\,s^{-1}}$ measurements. The feasibility of this proposal is addressed in Section 1.3.

The Hypertelescope Path (Labeyrie): Appendix B provides an introduction to the concepts and goals of the 'densified pupil multi-aperture imaging interferometer' or 'hypertelescope'. The proposal refers to the fact that space testing of versions as small as 20 cm mirror diameter, with mass below 0.5 kg, could be considered. Progressive versions could be used to study stellar surface resolution (20 cm apertures spanning 100 m in geostationary orbit); detection of exo-Earths at visible and infrared wavelengths (spanning a few hundred metres at L2); much larger versions will be needed to resolve surface features of exo-Earths.

Lamarck – an International Space Interferometer for Exo-Life Studies (Schneider): the proposal stresses the importance of the optical (rather than infrared) domain for space interferometry, and outlines a concept for a temporaily 'evolving' interferometric station, with the participation of other countries like China, Japan, India and Russia, employing an initial collecting area of around $40\,\mathrm{m}^2$, baselines above 3 km, a spectral range of 0.3–3 μm and $R = 100$. The mission strategy would be to detect Earth-like planets with baselines up to 1 km, imaging of the most promising candidates with very long baselines, then interferometer upgrades with subsequently-launched free flyers.

The resulting recommendations of the ESA Astronomy Working Group are contained in ASTRO(2004)18 of 19 Oct 2004. The 47 responses were assigned to three themes: (1) Other worlds and life in the Universe; (2) the early Universe; (3) the evolving violent Universe. The relevant part of the document is reproduced here verbatim:

1.1 From exo-planets to biomarkers

After the first discovery of an extra-solar planet in 1995, there has been steady progress towards detecting planets with ever smaller masses, and towards the development of a broader suite of techniques to characterise their properties. There is no doubt that this trend will continue into the next two decades, as substantial technological challenges are progressively overcome. After Corot will have opened the way to telluric planet finding, the Eddington mission would get a first census of the frequency of Earth-like planets. Gaia will deliver important insights into the frequency of giant planets; the existence and location of such planets is crucial for the possible existence of Earth-like planets in the habitable zone. Gaia will also further improve our understanding of the stellar and Galactic constraints on planet formation and existence.

The next major break-through in exo-planetary science will be the detection and detailed characterisation of Earth-like planets in habitable zones. The prime goals would be to detect light from Earth-like planets and to perform low-resolution spectroscopy of their atmospheres in order to characterise their physical and chemical properties. The target sample would include about 200 stars in the Solar neighbourhood. Follow-up spectroscopy covering the molecular bands of CO_2, H_2O, O_3, *and* CH_4 *will deepen our understanding* *of Earth-like planets in general, and may lead to the identification of unique biomarkers. The search for life on other planets will enable us to place life as it exists today on Earth in the context of planetary and biological evolution and survival. Being aware of the technical challenge to overcome the high brightness ratio between star and planet and the advancements in technology reached during the past few years by ESA studies, the AWG strongly and unanimously recommends the implementation of a mission addressing these objectives through a nulling interferometer for the wavelength range between 6–20 μm. Such a mission should be implemented around 2015, making Europe highly competitive in the field.*

The next step in this well-defined roadmap would be a complete census of all terrestrial extra-solar planets within 100 pc, for example through the use of high-precision astrometry. Longer-term goals will include the direct detection and high-resolution spectroscopy of these planets with large telescopes in IR, optical and UV wavelengths and finally the spatially resolved imaging of exo-Earths, leading to the new field of comparative exo-planetology.

The conclusions of the document state: *For the very first part of the 2015-2025 decade, two observatory-class missions are recommended: (1) a mid-infrared nulling interferometer for the detection and characterisation of Earth-like planets in the Solar neighbourhood. In order to ensure a timely implementation of such a mission, the AWG gives high priority to the continuation of the present fruitful technology program for this project, and strongly and unanimously recommends that all steps be taken to ensure that such a mission can be flown as early as possible in the 2015 time frame; (2) a far-infrared observatory, etc...*

The conclusions also comment: *The AWG reiterates its unanimous support to a rapid implementation of the Eddington mission, which would constitute an important intermediate step towards the scientific goals formulated in theme 1.*

3.4 Other Concepts and Future Plans

Although it is of course impossible to look forward a number of years and to predict the status then, more or less plausible novel (i.e., as yet unproven) methods might conceivably be applied for exo-planet studies.

The use of 'new' physical principles for the imaging of exo-planets may develop. Not long ago, it was realised that light (photons) may carry orbital angular momentum (in addition to the ordinary photon spin associated with circular polarization). Interference of such light may produce a dark spot on the optical axis, but high intensities outside (but still inside the 'classical' diffraction spot). By suitable manipulation of starlight, different amounts of angular momentum might be induced to light from the central star, relative to its nearby planet, thus enhancing the observable contrast by several orders of magnitude. For an introduction to light's orbital angular momentum, see Padgett et al. (2004); for a discussion of high-contrast imaging using such methods, see Swartzlander (2001); for reference in the context of exo-planet studies, see Harwit (2003).

3.5 Summary of Prospects: 2015–2025

The major space and ground-based experiments so far considered for the 2015–25 time-frame do not include survey missions beyond Kepler/Eddington and Gaia, but focus on the detection and characterisation of a few low-mass planets in the Solar neighbourhood.

The detection prospects are summarised in Table 8, compiled by Angel (2003), and include Darwin/TPF and OWL. An assessment of the S/N of planet detections with OWL has been made independently by Hainaut & Gilmozzi (ESO), and is in broad agreement with those in the table. The Darwin S/N assessments for both imaging and spectroscopy, detailed in Table 9, are also broadly in agreement with this summary table.

Accepting the (unproven) hypothesis that there are Earth-mass planets around solar-type stars within 10–20 pc, their detection and characterisation even with Darwin/TPF and/or OWL will be challenging. At this time it would seem appropriate to continue the search with both ground and space techniques, at least until their respective technical limitations and costs are better understood.

4 The Role of ESO and ESA Facilities

4.1 The Expected Direction of Research

As detailed in the previous sections, plans for the forthcoming decade are focused on surveys that attempt to detect large numbers of objects by various methods (transits, astrometry, microlensing). The aim is to obtain information on thousands of systems, and thus to characterise the population frequency of extra-solar planets according to mass, orbital radius, etc., essential for refining theories of planet formation and evolution.

Beyond 2015, programmes targeting further characterisation of the large-scale statistical distribution of planets do not (yet) exist, probably since the requirements for large-scale surveys of other aspects of planetary parameter space have not yet been carefully considered. Instead, post-2015 projects currently address the existence and characterisation of Earth-mass planets around a number of carefully selected candidate stars, both from ground and space, and questions related to habitability and the existence of life. Both ground and space approaches will be highly challenging and expensive, and their technical feasibility is still being evaluated.

A synthesis of prospects is presented in Figure 7, which tabulates the space (second column) and ground (fourth column) techniques, the resulting candidate detections (third column) and statistical knowledge (first column), and possibilities for follow-up observations.

In this section the following questions are addressed:

(a) what follow-up observations and facilities are required to characterise these systems more completely (Section 4.2);

(b) what does the resulting (statistical) knowledge of exo-planet distributions imply for the targeted observations of Darwin and OWL (Section 4.3);

(c) what information will be available, or should be anticipated, for a deeper astrophysical characterisation of the host stars of planetary systems (Section 4.4);

(d) what is the potential overlap amongst the major facilities currently planned or studied by ESO and ESA (Section 4.5);

(e) are there specific long-lead time space or ground facilities which should be considered to fill observational gaps anticipated over the next 10–20 years (Section 4.6);

(f) are there other considerations that ESO/ESA should investigate for proper interpretation of the data which will be generated by these two European organisations, or others, and which might limit the development of the field unless suitably coordinated (Section 4.7).

4.2 Follow-Up Observations

With reference to Figure 7, over the next 5–10 years ongoing or approved survey experiments are expected to generate:

(a) high-mass ($\sim M_{\rm J}$) candidates: some hundreds from COROT, Kepler and Eddington; thousands with Gaia astrometry and thousands of transiting systems with Gaia photometry; some hundreds from ongoing and future ground-based radial velocity surveys; and hundreds (possibly thousands) of hot Jupiters from ground-based transit surveys;

(b) low-mass ($\sim 1-3\,M_\oplus$) candidates: a small number of hot terrestrial planets from COROT around 2008; with tens to hundreds from Kepler expected to be available to the community after about 2010.

In principle, the information required for further characterisation of a detected planetary system is independent of the star or planet mass: as discussed elsewhere in this report: (a) radial velocity measurements of transit detections to eliminate false alarms due to grazing eclipsing binaries, triple stars, star spots, and false positives; (b) transit spectroscopy from ground or space for the determination of atmospheric properties; (c) the combination of transit or astrometry data with radial velocity information allowing the determination of the true mass of the planet; (d) photometric or spectroscopic information needed to characterise the parent star; (e) follow-up imaging of transiting candidates with high spatial resolution adaptive optics to minimise the possibility that the object is actually multiple, or that a foreground or background binary system is causing the dimming of the light; (f) all the above will provide candidates for ground-based imaging by VLT, VLTI, OWL, etc.

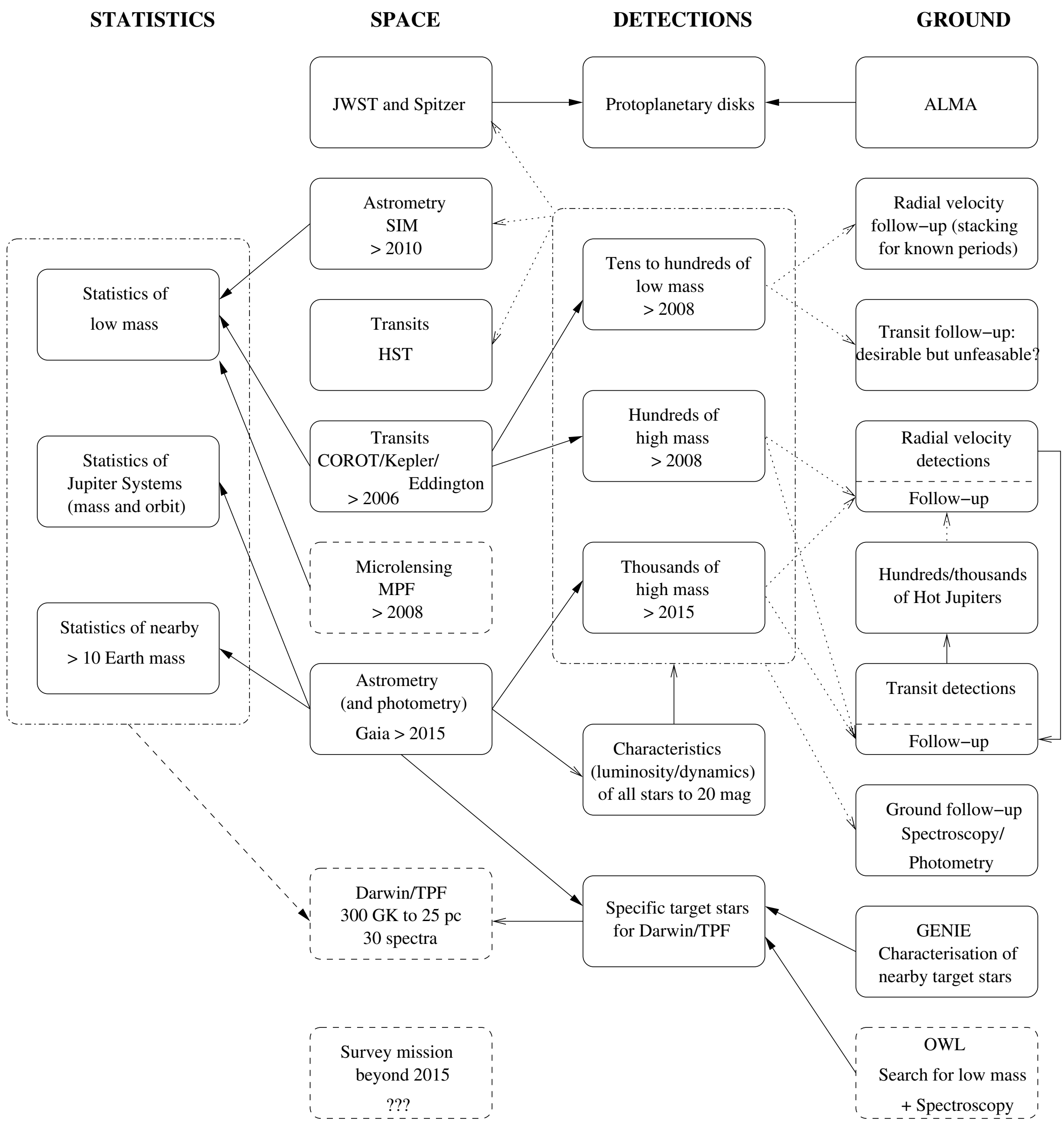
For microlensing candidates, no follow-up observations are generally possible. Nevertheless, due to the relative proper motion, the lens star will increase its angular separation to the source star and become visible after some time. One case is known: MACHO LMC–5, in which the lens star was imaged after about 8 years or so (Alcock et al., 2001). So in principle, there exists a possibility to study the host star of a microlensing planet, depending on the mass/apparent brightness of the lensing (i.e., host) star, and on the relative transverse velocity.

In practice, the problem is distinct for high-mass or low-mass planets.

4.2.1 High-Mass Planets

For high-mass objects (of order $1\,M_{\rm J}$), ground-based follow-up transit measurements will generally be technically feasible with the current generation of instruments. COROT, Kepler, Eddington, Gaia, OGLE, possibly HST, and the ground-based transit networks will supply thousands of targets which can be followed from the ground. Small telescopes, preferably robotic, and substantial amounts of observing

Figure 7: Links between detection methods in space (second column) and ground (fourth column), resulting statistical information (first column) and candidate detections (third column). Experiments which are not approved are shown as dashed boxes. The large dash-dotted boxes show the cumulative statistical knowledge, and the cumulative candidate lists respectively. Solid arrows show the candidates resulting from a particular observation. Dotted arrows indicate the follow-up observations needed. Note that the Kepler detections will all be in the northern hemisphere, and thus unobservable from ESO.



time will be required. Existing transit measurement facilities and amateur networks could contribute, although some new dedicated provision for follow-up is probably needed, in particular enlarging networks in longitude to significantly improve the efficiency of ground-based transit observations.

Radial velocity follow-up will be needed for all high-mass candidates, of which Gaia will generate a very large number. Thousands of the more massive planets could be observed by ground-based radial velocity instruments, assisting the determination of multiple planets, relative orbital inclinations, etc. ESO could consider a coordinated large-scale follow-up of such radial velocity observations, and whether additional facilities will be needed. An assessment of telescope time/aperture needed for these projects has not been made — probably a combination of existing facilities and larger dedicated instruments would be needed.

4.2.2 Low-Mass Planets

Low-mass (of order $1\,M_\oplus$) planets will hopefully be detected by Kepler and Eddington, perhaps in moderately large numbers (some hundreds).

They will typically be too low-amplitude for ground-based photometric follow-up, which in any case are unlikely to improve on the S/N of weak transit events detected by Kepler or Eddington – these missions will have years of lightcurves on a star, and if the signal is still weak after phasing and adding all data, it will be difficult to improve from the ground in a reasonable time. This is a potential problem, since such follow-up observations will be needed: (i) to confirm the reality of the lower S/N detections; (ii) to search for planetary periods for candidates for which only one transit is detected; (iii) to confirm candidate detections for which two or possibly more transits were detected (since periods and transit times are known, ground-based follow-up may be more feasible); (iv) to search for period changes due to planetary moons etc.; (v) to characterise the transit systems in terms of chemical abundances. Probably the only prospect is follow up with HST and/or JWST (see Section 2.2.1) for transits, and possibly SIM for astrometry, although many of the transit candidates will be too distant even for these instruments.

Radial velocity measurements are again needed in principle to supplement the orbital information. Improvements in radial velocity precision for transits may be achieved by the stacking of repeated observations at the known planet period, as described in Section 1.3. If Eddington is approved (or for the study of Kepler candidates), the development of new telescope facilities should be considered, such as a high-precision spectrograph (like HARPS) based on an 8-m (or larger) telescope. Given the low expected surface density of accessible candidates, it is unlikely that a multi-object instrument would be effective and so a highly-optimised single object instrument offering a precision of $\sim 1\,\mathrm{m\,s^{-1}}$ would be preferred. The HARPS detection of a $14\,M_\oplus$ planet demonstrates that it may be possible to characterise all the exo-planets detected by COROT (massive Earths with short periods) in this way.

4.2.3 Summary of Follow-Up Facilities Required

To summarise the requirements for these follow-up programmes, the following facilities will be needed:

(a) high-precision radial velocity instrumentation for the follow-up of astrometric and transit detections, to ensure the detection of a planet by a second independent method, and to determine its true mass. For Jupiter-mass planets, existing instrumentation may be technically adequate but observing time may be inadequate; for Earth-mass candidates, special-purpose instrumentation (like HARPS) on a large telescope, would be required. Requirements for automated telescopes for precise radial-velocity measurements have been discussed by Pepe & Mayor (2004);

(b) photometric monitoring of large numbers of high-mass planet candidates coming from space experiments: a combination of existing and new facilities will be needed;

(c) very high-resolution (adaptive optics) imaging of transit candidates to reject the 'false-positives' generated by confusing sources;

(d) photometric and spectroscopic characterisation of all candidate planetary systems, providing fundamental stellar parameters such as temperature, gravity and metallicity. A combination of planned (Gaia) and new (spectroscopic survey) instrumentation will probably be required;

(e) follow-up of candidates from microlensing studies will be necessary to identify host-star properties that maximise the probability of finding a planetary system.

A first (and incomplete) assessment of necessary telescope time can be made as follows:

(a) for the photometric monitoring: assuming a telescope optimized for fast photometric measurements (i.e. with low overhead), up to 6 measurements per hour can be expected, i.e. 15 000 measurements per year. A dedicated instrument, following the concept of the 'Gamma-Ray burst Optical/Near infrared Detector' (GROND, http://www.mpe.mpg.de/~jcg/GROND/), permitting simultaneous measurements in up to 7 photometric bands, could be duplicated for a 4-m and for a 1–2-m telescope in order to optimize the aperture of the telescope with the brightness of the target. The photometric monitoring would then be performed in about 1 year (full time) assuming two telescopes.

(b) for the radial velocity measurements: assuming an instrument like HARPS after optimization for fast observations, 4–5 stars could be measured each hour (i.e. about 5 minutes preset and overhead, and 5–10 minutes exposure), thus 40–50 measurements per night, or up to 15 000 measurements per year, assuming the instrument is operated full time. This follow up will then require this telescope for a few years in order to measure each star at least 3–4 times at different orbital phases.

4.3 Statistics of Exo-Planets: Implications for Darwin/OWL

As noted under Appendix A, the McKee-Taylor Decadal Survey Committee (McKee & Taylor, 2000) qualified its endorsement of the TPF mission with the condition that the abundance of Earth-size planets be determined prior to the start of the TPF mission. A similar strategy will be desirable for Darwin.

The various missions and experiments discussed throughout this report will contribute to detailed statistical information of planetary distributions over different mass ranges, but cannot provide complete information on the occurrence of Earth-mass planets in the Solar neighbourhood (say, to 15–20 pc) in advance of the planned Darwin launch: transit measurements are highly incomplete, the Gaia lower mass limit is above $10\,M_\oplus$, and the SIM survey will presumably also be incomplete down to the levels of $1–2\,M_\oplus$. Gaia and SIM may assist in identifying nearby stars accompanied by Jupiter-type planets (i.e., Jupiter mass in a Jupiter orbit), which may be a representative pre-requisite for the development of life. Nano-arcsec astrometry could provide the necessary information in principle, but practical implementation lies some years in the future.

Nevertheless the SIM and COROT/Kepler/Eddington results should clarify whether Earth-mass planets are common or not. If they are not detected, and therefore not common, Darwin's task in identifying Earth-mass planets within 20–30 pc will be even more challenging. Then, either additional identification strategies are required (for example, the development of an Antarctic facility dedicated to the purpose, such as a coronographic ELT in the visible/near infrared, or a large interferometer in the thermal infrared), or it is accepted that a significant fraction of Darwin observations is devoted to a search for its own spectroscopic candidates. Thus Darwin could be launched relying on a statistical estimate of the number, and size, of the terrestrial planets that are expected around the stellar target list, combined with the GENIE results on levels of exo-zodiacal emission. If statistics indicate that the number of Earth-mass planets accessible to Darwin is of the order of several tens, this strategy would be acceptable. Conversely, it could also be argued that a null result from a 200-star survey would be a valuable scientific result in its own right.

Current understanding suggests that metallicity is a crucial factor influencing the formation of planets. Higher metallicity therefore seems to be the most promising stellar characteristic that would indicate whether a star is likely to harbour planets. The recently published Geneva-Copenhagen survey (Nordström et al., 2004), mostly aimed at stellar kinematics, has also provided valuable information on metallicities for over 14 000 F and G type dwarf stars using Stromgren photometry. A more detailed measurement of stellar parameters, including metallicities, requires medium- to high-resolution spectra over a large wavelength range. For extra-solar planet research an accurate knowledge of the properties of the host star is essential, even more so when looking for the weak signatures of the planetary atmosphere. A full spectral characterisation of stars in the solar neighbourhood would be a valuable step towards a target list for major projects such as TPF, Darwin or OWL.

4.4 Astrophysical Characterisation of Host Stars

Several thousand planetary systems should be discovered by a combination of COROT, Kepler, Eddington, SIM and Gaia over the years 2006–2015. There will be a need for detailed astrophysical characterisation of large numbers of stars (some tens of thousands), in both the northern and southern hemispheres. Specifically:

(a) physical characteristics of the host star via photometry: it will be important to characterise, homogeneously, luminosity ($T_{\rm eff}$, $\log g$), metallicity, and micro-variability. Large-scale multi-colour, multi-epoch photometry for this purpose may be available from Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) or LSST (Large Synoptic Survey Telescope) and from Gaia's 11-band multi-colour photometry, although not before 2012;

(b) physical characteristics of the host star via spectroscopy: the goal is again to determine the spectroscopic parameters of the central star: $T_{\rm eff}$, $\log g$, [Fe/H]. Medium-high spectral resolving power is needed (20 000–60 000) in the visible range;

(c) spatial distribution and kinematics: Gaia will provide highly-accurate distances essential for luminosity calibration (e.g., 1% at 1 kpc at 15 mag), characterised as a function of the local environment (e.g., for stars within the core or halo of open clusters), and kinematic motions (e.g., with respect to the Local Standard of Rest, velocity with respect to the Galactic mid-plane, etc.). This characterisation is important because of possible links with habitability (as discussed in Section 1.2).

(d) kinematic radial velocities for fainter stars. Hipparcos would have greatly benefited from a coordinated acquisition of radial velocities from the ground. Key programmes went part way towards this, but only for half the sky, for a subset of spectral types, and on a schedule out of phase with the Hipparcos Catalogue publication in 1997—the Geneva-Copenhagen survey of 14 000 F and G dwarfs has just been published (Nordström et al., 2004). Gaia partly addresses the problem by acquiring radial velocities on-board, but higher precision and a fainter limiting magnitude would demand a concerted and coordinated campaign on the ground.

With the caveats on the time-scales of data availability, planned surveys (Gaia, if not others) should generally provide detailed astrophysical characterisation of the host stars of all detected systems, with the possible exception of kinematic radial velocities for faint stars ($>$ 20 mag), and a dedicated spectral survey.

4.4.1 A Dedicated Spectral Survey

ESO has capabilities to perform a full spectral characterisation of all F–K type stars in the southern hemisphere within a radius of say 50 pc. Facilities at ESO could be used to obtain a complete spectrum of the stars from the atmospheric cut-off to 5 μm. By combining the Echelle spectrographs FEROS (2.2-m), UVES, and CRIRES the complete wavelength range can be observed at $R \sim 50\,000$. A cursory study shows that such a project could be undertaken at the level of a (very) large programme, of the order of 100 nights in total. Selecting stars within 50 pc (Hipparcos distances) and at declination south of 30 degrees North, a total of about 2500 stars would have to be observed. 75% of these have V magnitudes between 5 and 9 making them ideal targets for FEROS, while the remaining fainter ones would be observed with UVES. Using the ESO exposure time estimators for the respective instruments we found that a S/N of about 100 will be achieved within minutes. Using about 110 hr of time on FEROS and about 40 hr on UVES per period to obtain the spectra from 350–980 nm the optical survey could be completed within two years with existing facilities, assuming an ESO 'Large Programme' using only late twilight and periods of bright moon and/or poor seeing. CRIRES is being assembled at this point, therefore no estimate of the time required for the infrared observation is given here. Because the majority of stars are rather bright a very substantial fraction (30–50%) of the stars can be observed during twilight while the remainder can be observed during bright time. It is evident that a high degree of homogeneity of spectral data needs to be achieved across the full set of stars in order to achieve the scientific goals of the project. In particular the combination of spectra calls for excellent calibration across instruments. To this end the ECF's Instrument Physical Modelling Group which is involved in the calibration of instruments on HST and at ESO is prepared to make major contributions thereby ensuring maximum quality of the data and the resulting high level products.

A comparable 'Nearby Stars' project (PI: R.E. Luck) is being conducted in the northern hemisphere (http://astrwww.cwru.edu/adam/) using the McDonald 2.1-m Struve reflector and the Sandiford Echelle Spectrograph.

A dedicated survey would provide data useful for other applications in astrophysics. Results would include a very fine spectral library which, combined with e.g. Gaia information on the luminosity function and kinematics, would be very powerful.

4.5 Potential Overlap and Competition

Eddington and Kepler

The arguments for undertaking the Eddington mission are unchanged from the time that the ESA Astronomy Working Group placed it at the top of the list of astronomy projects to be undertaken if financing can be made available. Essentially, Kepler is designed to study a single low-latitude target field and thus a single population of stars, in a limited mass range. In the same way that the star formation history of the Galaxy cannot be ascertained by observing a single field, the acceptance of Kepler results as being of general applicability to the complete Galaxy is questionable. This is exemplified by the absence of planets in 47 Tuc, and is a question that can only be resolved by further observations.

Without any further mission dedicated to terrestrial planet searches, there will be no real understanding of the distribution of such planets in general (e.g., in other parts of the Galaxy or in clusters), and the number of targets discovered by Kepler may in any case be very small. Eddington would observe stars in a variety of environments, i.e., field stars and stars in open clusters, and will thus consolidate the search for planets across different stellar parameters (including metallicity, age, mass, binary status, density of surrounding stellar population, etc.).

More generally, experiments need repeatability: single experiment results always provoke more questions, and if the results are controversial it is only reasonable that they are checked independently. Having just one mission aimed at the detection of terrestrial planets appears risky and inadequate, in particular considering the effort being made for future missions that aim at studying these planets (Darwin/TPF). The present working group emphasises the value of aiming to launch such a mission at the earliest opportunity, preferably before 2010. Should it turn out that it is only possible to launch Eddington significantly later, ESA should consider a larger-scale post-Kepler mission on a longer time schedule.

OWL and Kepler/Eddington

The OWL science case is currently not so much based on finding Earth-like planets, but rather on imaging or spectroscopy of nearby candidates detected by other means. To this extent OWL's primary science case is as a follow-up instrument. On the other hand there are no prospects other than Darwin/TPF for finding all nearby Earth-mass planets (transits can only discover a small fraction), so its use for Earth-mass planet searches in a survey-type mode would be valuable, and should add to its contribution to the field. Such a survey might be undertaken during the mirror-filling phase, although detailed feasibility studies of this approach have not yet been made.

OWL/Dome C versus Darwin/TPF

As summarised in Section 3.1.2 and Table 8, appropriate Antarctic observations could at least partially compete with some aspects of the Darwin/TPF missions. However, some key spectral regions are accessible only from space, e.g. O_3 at $9.6\,\mu$m and CO_2 at $15\,\mu$m. Trade-offs would depend on the number of objects visible, the S/N ultimately attainable from Darwin, and the accessible spectral range and the resulting scientific information that can be inferred for exo-planetology and exobiology. Further investigations will be needed in order to understand whether such Antarctic-based observations could be considered as realistic in the medium term.

4.6 Open Areas: Survey Mission Beyond Kepler/Eddington

The absence of specific survey missions beyond 2015 noted in Section 4.1 can only be justified once all interesting targets in the sky to be studied in the future have been discovered. For small terrestrial planets, the Kepler mission is the only approved discovery mission. Even with Eddington, statistics of the occurrence of Earth-mass planets will still be poorly known, and the need for a larger, more performant, space transit survey seems already rather compelling. A case could also be made for an all-sky transit survey from space, in order to find the nearest transiting terrestrial planets, facilitating follow-up with astrometry and spectroscopy. The arguments presented in Section 3.3, 'Understanding the Planetary Population of our Galaxy', also draw attention to a lack of further search programmes for terrestrial planets beyond Kepler.

4.7 Other Considerations

4.7.1 Fundamental Physical Data

It is not evident that present knowledge of basic atomic data is adequate to understand the high-resolution spectra of normal host stars over the broad wavelength region discussed in Section 4.4.1, and the spectral signatures of planets and their atmospheres. Preliminary investigations suggest that there is a need for improved atomic and molecular lines particularly in the near infrared. To illustrate the point and the potential risk of inadequate atomic data we give two examples: (i) Li in low mass post-AGB stars; expanded wavelength tables for Ce have shown that the line at 670.8 nm previously identified with (slightly redshifted) Li is coincident with a Ce II line at 670.8099 nm. Abundance analysis subsequently showed that for all practical purposes no Li is present in these stellar photospheres (Reyniers et al., 2002). This is an important finding for stellar evolution and nucleosynthesis since an elaborate mechanism had to be evoked in order to explain the presence of Li in these evolved stars; (ii) variability of the fine structure constant: evidence from the absorption features in distant quasars suggested a variability of the fine structure constant over time. Originally, these studies had been hampered by limited accuracy of laboratory wavelengths for the relevant species (Pickering et al., 2000). Most recently a further complication introduced by the sensitivity to the abundance of heavy isotopes has been described for Mg (Ashenfelter et al., 2004), where uncertainties in the isotope ratios might imitate a variation of the fine structure constant at the observed level. Nearer to the issues of exo-planets, the debate about the nature of Jupiter's interior centres on the (unknown) equation of state of H/He mixtures at high pressures.

Regardless of the exact details these examples illustrate that the lack of accurate and reliable atomic data can lead to serious misinterpretation of astrophysical data. When dealing with fundamental issues such as the properties of extra-solar planets and their suitability for supporting life such pitfalls can be rather embarrassing and damaging to the credibility of the field. In order to assess the current situation properly, further consultation will be needed between the astronomical community and the relevant atomic and molecular physics community involved in the laboratory work. Links between these communities are also being investigated in the context of the Virtual Observatory.

4.7.2 Fundamental Planetary Data

The solar system research community has the best knowledge of the only planetary system studied in detail, with extensive data archives like the Planetary Data System (PDS). For extra-solar planet research full use of that information must be made without being limited by it. Most of the planetary systems found so far are quite different from ours. Items of particular relevance might be: (i) distribution of minor bodies and dust, relevant for zodiacal light; (ii) mass radius relation for various kinds of planets; (iii) reflective properties of different planetary surfaces (gaseous/solid, rock/ice) in particular integrated over the sphere (and thus the influence of weather); (iv) spectral signatures of planetary atmospheres; (v) mass-loss from atmospheres; documented by planetary probes for Mars, indication for mass loss has also been found in HST observations of the transit of HD 209458; (vi) signatures of volcanism, like SO_2 (cf. Earth and Io).

Scientific results on solar system bodies and extra-solar planets are presented at various conferences of both communities, which in part have already established 'cross-discipline' sessions to support the exchange of knowledge between the two fields (e.g., the EGU and DPS). ESO and ESA might consider fostering the exchange of information and collaboration by organising joint cross-disciplinary workshops, including ESA's Earth observation community. Such dedicated workshops could aim at the specific needs of extra-solar planet research and serve to define the needs for further observations of solar system bodies (e.g., atmospheres of planets and moons). In addition, building a data base collecting, for example, the spectra on planets, moons and minor bodies in our solar system as a reference for extra-solar planets could be discussed within both communities at such dedicated meetings.

4.7.3 Amateur Networks

As described above, thousands of candidate planets will be discovered by ongoing surveys both from the ground and in space. Follow-up of all these candidates will be essential in order to verify their existence and to derive additional information about their properties. Observations of transits in particular will be valuable for candidates found by radial velocity or astrometric measurements. Dedicated (groups of) amateurs with state of the art equipment at reasonably large (>60 cm) telescopes could contribute in this area. The AAVSO is already calling on its observers to engage in such activity. Very recently, a dedicated campaign to observe possible transits of GJ 876b in the system IL Aqr was announced spanning a ten-hour period starting 21 Oct 2004 (http://www.aavso.org/news/ilaqr.shtml). ESO and ESA could take a leading role here by establishing and coordinating a dedicated Amateur Transit Network, an interesting opportunity for scientific reasons as well as for its potential for public outreach.

Scientifically, the most attractive aspect is that a global network (10–20 individual observatories) could provide very significant amounts of observing time and excellent time coverage. The latter is also essential for finding planetary signatures in microlensing events. Such a network probably will be the most cost-effective and efficient way to achieve a large increase in follow-up observations of candidates. The major challenge is to ensure that observations from different sources can successfully be combined for analysis. To achieve the required homogeneity, ESO/ESA could consider the use of common hardware (CCD and filters) by the members of the network and possibly software support. Relatively modest expenditures would be required to equip each participating observatory with a high-quality photometric system, very beneficial in terms of data quality. Although the effort required to coordinate such a network should not be underestimated, if properly coordinated and supported, an ESO/ESA amateur transit network could provide a cost-effective way to substantially increase the capablility for follow-up observations of candidates. Such an increase seems necessary in order to keep up with the demand projected to materialise over the next decade.

Sky & Telescope (December 2004, p18) reported that only eight days after the transiting system TrES–1 had been announced, a transit was observed by a Belgian amateur as well as by two observers from Slovenia. The first transit system HD 209458 is fairly bright at $V = 7.6$ mag, but TrES–1 is only 11.8 mag. The detector hardware used for the discovery of TrES–1 is quite comparable to what advanced amateurs have. One main difference is the software which enables the monitoring of thousands of stars, and therefore acceptable chances for discovery. In this context, one aspect of Section 2.1.2 is recalled: Holman & Murray (2005) and Agol et al. (2005) describe how repeated observations of transits may lead to the discovery of Earth-mass planets: the gravitational influence of the small planet will induce pertubations in the orbit of the much larger planet causing the transit; over a period of time this will lead to a shift of the observed transit times on the order of minutes. The effect is more pronounced for long-period massive planets, with low-mass companions in orbital resonance.

Involvement of amateurs in extra-solar planet research also opens a very attractive field in terms of public outreach and eduction. The general public clearly is very interested in the topic of extra-solar planets. The subject therefore is well suited to provide information and eductational material explaining the prospects and limitations of searches for extra-solar planets to the public and decision makers. Given the very substantial investments required to realise the next generation of extremely large telescopes, astronomy should make a dedicated effort to take advantage of this overlap of public and research interest. While an outreach effort on extra-solar planets will be worthwhile in its own right, we expect that an outreach effort centered around an amateur (public) involvement in science will be much more effective thanks to its novelty and emotional appeal. In order to get some feedback from the amateur community directly one of us (FK) gave a presentation at the 8 November 2004 meeting of the astronomy club 'Max Valier' in Bolzano, Italy. The club has more than 100 members and is well-equipped with an 80 cm telescope and modern CCDs. Their new observatory at Gummer was built with funds of the local government and is now run as a public observatory (http://www.sternwarte.it) with an extensive program of tours and observing sessions for schools and the general public. Further details of this meeting, and a more detailed proposal for follow-up, are available.

5 Recommendations

Europe has already established leadership in major areas of the exo-planet field, including radial velocity (HARPS), transit searches (COROT), and astrometry (Gaia).

The first goal of future actions should be to take full advantage of this situation, with an offensive policy to optimize the scientific return of instruments already built or foreseen in the near future [the ongoing or planned ESO instrument programmes (HARPS, UVES, CRIRES, OmegaTranS, PRIMA, GENIE, Planet Finder, etc.) are not considered further here].

The second goal is to prepare new initiatives. Suggested directions are:

1. ESA

1.1. Eddington: provide a clearer message to the community about the plans and schedule for an Eddington-type exo-planetary mission [Section 2.2.1].

1.2. Gaia: recognise that the highest accuracy will supply the most comprehensive information on low-mass planets in the Solar neighbourhood (down to about $10\,M_\oplus$), thus assisting the identification of targets for Darwin/OWL/PRIMA, and the largest number of detections, scaling as the third power of the accuracy [Section 2.2.2].

1.3. Darwin: maintain the research and development plan for this key project in the domain of exo-planet science at high priority, consistent with the current 2015 target launch date, cf. TPF-C launch planned for 2014 [Section 3.2].

1.4. JWST: support the 'Astrobiology and JWST' panel recommendations, to ensure that JWST can follow up low-mass transits discoveries [Section 2.2.4].

1.5. Encourage the community to submit mission proposals covering the important themes in Section 3.3: e.g. a future transit survey mission significantly more performant than currently planned; an all-sky transit mission; a UV spectroscopic mission for transit spectroscopy; astrometric detection of Earth-mass planets out to 20–30 pc, etc. [Section 3.3].

2. ESO

2.1. Support experiments to improve radial velocity mass detection limits, e.g. based on experience from HARPS, down to those imposed by stellar surface phenomena [Section 1.3].

2.2. Characterise nearby potential planet host stars, e.g. $T_{\rm eff}$, log g, [Fe/H], M, radius, etc. [Section 4.4].

2.3. Improve the capabilities of main-stream VLT instruments for high cadence, high S/N transit spectroscopy in the visible and infrared [Section 2.1.2].

2.4. Evaluate observation time for follow-up observations over the next 10 years of transit candidates obtained by space missions (COROT, Kepler, Eddington-like) and ground-based observations, including high-resolution imaging and photometry, on small to very large telescopes [Section 4.2.3].

2.5. In addition to the use of OWL as a follow-up facility, consider prospects for OWL searches for Earth-mass planets in the solar neighbourhood, including during the filling phase [Section 3.1.1].

2.6. Investigate the astrometric capabilities of OWL, possibly leading to the inclusion of an astrometric facility in the instrumentation plan [Section 3.1.1].

3. ESO–ESA – Joint Initiatives

3.1. Consider radial velocity follow-up of COROT (and possibly Kepler or Eddington-type missions – but note caveats of Kepler visibility) transit candidates . This would involve hundreds of targets and requires: (1) a major time allocation of La Silla 3.6-m telescope to HARPS; (2) probably an instrument with a precision similar to HARPS but on a larger telescope [Section 4.2.3].

3.2. Consider facilities for radial velocity follow-up of the large number of candidates (20–30 000) from Gaia, requiring observing time on relatively small, possibly robotic, telescopes for a few years of full-time operations [Section 4.2.3].

3.3. Consider the photometric (transit) monitoring of large number of high-mass planet candidates which will come from space experiments [Section 4.2.3].

3.4. Support valid observing time requests for preparatory work to space exo-planet missions, e.g., field characterisation for an Eddington-like mission [Section 4.2.3].

3.5. Evaluate the prospects of implementing a small interferometric array, along the lines of GENIE, at Dome C/A, given that it could radically change the capabilities of ELTs if (a second) OWL were located there [Section 3.1.2].

3.6. Consider coordination of amateur networks, along the lines of AAVSO, for the follow-up of hot Jupiters detected from ground transit surveys, from Gaia astrometry and photometry, and for surveys for longer-period objects [Section 4.7.3].

3.7. Foster cooperation between the solar system research community and the extra-solar planets community, e.g. by supporting or establishing joint meetings of both communities addressing common topics, such as formation, comparative planetology, emergence and evolution of life on Earth and elsewhere, etc. [Section 4.7.2].

3.8. Coordinate exo-planet public communication, with some common 'code of conduct', e.g.: (i) no press release without a supporting scientic paper; (ii) claims should not be overstated, with support sought from external organisations or universities; (iii) retractions should be posted in the same form to retain credibility.

Index to ESA and ESO facilities:

Descriptions of each experiment or facility are given as follows:

ESA:

COROT: see Section 2.2.1

Eddington: see Section 2.2.1

Gaia: see Section 2.2.2

HST (ESA/NASA): see Section 2.2.1

JWST (ESA/NASA): see Section 2.2.4

ESO:

ALMA: see Section 2.1.6

CRIRES: see Section 2.1.2

GENIE: see Section 3.2.2

HARPS: see Section 2.1.1

NAOS-CONICA: see Section 2.1.6

OWL: see Section 3.1.1

Planet Finder: see Section 2.1.6

PRIMA: see Section 2.1.6

VLTI: see Section 2.1.6

NASA/Other:

FAME/AMEX/OBSS: see Section 2.2.2

JASMINE (Japan): see Section 2.2.2

Kepler: see Section 2.2.1

MPF/GEST: see Section 2.2.3

SIM: see Section 2.2.2

SOFIA: see Section 2.2.4

Spitzer (ex-SIRTF): see Section 2.2.4

A Space Precursors: Interferometers, Coronographs and Apodizers

The McKee-Taylor Decadal Survey Committee (McKee & Taylor, 2000) qualified its endorsement of the TPF mission with the condition that the abundance of Earth-size planets be determined prior to the start of the TPF mission. Many ideas for scientific and technological precursors for TPF have been examined. The main contenders are summarised here for completeness, although with the recent (April 2004) NASA announcement on TPF strategy, it seems unlikely that any of these concepts will be developed further:

Eclipse (coronography) is a proposed NASA Discovery-class mission to perform a direct imaging survey of nearby planetary systems, including a complete survey for Jovian-sized planets orbiting 5 AU from all stars of spectral types A–K within 15 pc of the Sun (Trauger et al., 2003). Its optical design incorporates a telescope with an unobscured aperture of 1.8 m, a coronographic camera for suppression of diffracted light, and precision active optical correction for suppression of scattered light, and imaging/spectroscopy. A three-year science mission would survey the nearby stars accessible to TPF. Eclipse may be resubmitted for NASA's Discovery round in 2004.

Jovian Planet Finder (JPF) was a MIDEX proposal to directly image Jupiter-like planets around some 40 nearby stars using a 1.5-m optical imaging telescope and coronographic system, originally on the International Space Station (ISS) (Clampin et al., 2002). Its sensitivity results from super-smooth optical polishing, and should be sensitive to Jovian planets at typical distances of 2–20 AU from the parent star, and imaging of their dusty disks – potentially solar system analogues. A 3-yr mission lifetime was proposed.

Extra-Solar Planet Imager (ESPI) is another proposed precursor to TPF (Lyon et al., 2003). Originally proposed as a NASA Midex mission as a 1.5×1.5 m^2 apodized square aperture telescope, reducing the diffracted light from a bright central source, and making possible observations down to 0.3 arcsec from the central star. Jupiter-like planets could be detected around 160–175 stars out to 16 pc, with $S/N > 5$ in observations lasting up to 100 hours. Spectroscopic follow-up of the brightest discoveries would be made. The Extra-Solar Planet Observatory (ExPO) is a similar concept proposed as a Discovery-class mission (Gezari et al., 2003).

Self-luminous Planet Finder (SPF) is a further TPF precursor under study by N. Woolf and colleagues, aiming at the search for younger or more massive giant planets in Jupiter/Saturn like orbits, where they will be highly self-luminous and bright at wavelengths of 5–10 μm, where neither local nor solar system zodiacal glow will limit observations. SPF will demonstrate the key technologies of passive cooling associated with interferometric nulling and truss operation that are required for a TPF mission. SPF targets young Jupiter-like planets both around nearby stars such as ϵ Eri, and around A and early F stars.

Fourier-Kelvin Stellar Interferometer (FKSI) is a concept under study at NASA GSFC (Danchi et al., 2003). It is a space-based mid-infrared imaging interferometer mission concept being developed as a precursor for TPF. It aims to provide 3 times the angular resolution of JWST and to demonstrate the principles of interferometry in space. In its minimum configuration, it uses two 0.5-m apertures on a 12.5-m baseline, and predicts that some 7 known exo-planets will be directly detectable, with low-resolution spectroscopy ($R \sim 20$) possible in favourable cases.

Optical Planet Discoverer (OPD) is a concept midway between coronography and Bracewell nulling (Mennesson et al., 2003).

Phase-Induced Amplitude Apodization (PIAA, Guyon (2003)) is an alternative to classical pupil apodization techniques (using an amplitude pupil mask). An achromatic apodized pupil is obtained by reflection of an unapodized flat wavefront on two mirrors. By carefully choosing the shape of these two mirrors, it is possible to obtain a contrast better than 10^9 at a distance smaller than $2\lambda/d$ from the optical axis. The technique preserves both the angular resolution and light-gathering capabilities of the unapodized pupil, and claims to allow efficient detection of terrestrial planets with a 1.5-m telescope in the visible.

Occulting masks are another approach to tackle in a conceptually simple manner the basic problem of how to separate dim sources from bright ones, and have been considered as precursor missions to Darwin/TPF. Interest in this approach at NASA level currently appears limited.

UMBRAS (Umbral Missions Blocking Radiating Astronomical Sources) refers to a class of missions (Schultz et al., 2003), currently designed around a 4-m telescope and a 10-m occulter, with earlier concepts including a 5–8 m screen (CORVET), or as NOME (Nexus Occulting Mission Extension) a modification to Nexus, itself foreseen as a test of technologies for JWST.

BOSS (Big Occulting Steerable Satellite (Copi & Starkman, 2000)) consists of a large occulting mask, typically a 70×70 m^2 transparent square with a 35 m radius, and a radially-dependent, circular transmission function inscribed, supported by a framework of inflatable or deployable struts. The mask is used by appropriately aligning it with a ground- or space-based observing telescope. In combination with JWST, for example, both would be in a Lissajous-type orbit around the Sun-Earth Lagrange point L2, with the mask steered to observe a selected object using a combination of solar sailing and ion or chemical propulsion. All but about 4×10^{-5} of the light at 1 μm would be blocked in the region of interest around a star selected for exo-planet observations. Their predictions suggest that planets separated by as little as 0.1–0.2 arcsec from their parent star could be seen down to a relative intensity of 1×10^{-9} for a magnitude 8 star. Their simulations indicate that for systems mimicking our solar system, Earth and Venus would be visible for stars out to 5 pc, with Jupiter and Saturn remaining visible out to about 20 pc.

B Beyond 2025: Life Finder and Planet Imager

Within NASA's Origins Program HST, Spitzer and others are referred to as 'precursor missions', with SIM and JWST as 'First Generation Missions' leading to the 'Second Generation Mission' TPF which will begin to examine the existence of life beyond our Solar System. Once habitable planets are identified, a 'Life Finder' type of mission would expand on the TPF principles to detect the chemicals that reveal biological activities. And once a planet with life is found, 'Planet Imager' would be needed to observe it. These 'Third Generation Missions', Life Finder and Planet Imager, are currently just visions because the required technology is not on the immediate horizon. Short descriptions are included here for completeness.

Life Finder: Taking pictures of the nearest planetary system (Darwin/TPF) is considered to be a reasonable goal on a 10-year timescale, with low-quality spectra a realistic by-product. Life Finder, which would only be considered after Darwin/TPF results are available, and once oxygen or ozone has been discovered in the atmosphere, would aim to produce confirmatory evidence of the presence of life, searching for an atmosphere significantly out of chemical equilibrium, for example through its oxygen (20% abundance on Earth) and methane (10^{-6} abundance on Earth). Some pointers to the technology requirements and complexity of Life Finder have been described in the 'Path to Life Finder' (Woolf et al., 2001). Given that Darwin/TPF will take low-resolution low-S/N spectra, a large area high angular resolution telescope will be needed for detailed spectral study in order to confirm the presence of life. Recalling that the target objects will be as faint as the Hubble Deep Field galaxies, buried in the glare of their parent star some 0.05–0.1 arcsec away, the light collecting area of Life Finder will have to be substantially larger than TPF's 50 m^2: a useful target is 500–5000 m^2. One of the primary technical challenges will be to produce such a collecting area at affordable cost and mass.

The required development of new low mass and better wavefront optics, coronography versus nulling, pointing control by solar radiation pressure, sunshield, vibration damping, and space assembly, were addressed by Woolf et al. (2001). According to their study, a 'mini-Life Finder' might be a 50×10 m^2 telescope, made with 12 segments of 8.3×5 m^2, made of 5 kg m^{-2} glass, piezo-electric controlled adaptive optics, and a total mass (optics and structure) of about 10 tons. Cooling would be by an attached sunshade also used for solar pressure pointing, in a 'sun orbiting fall away' orbit to avoid the generation of thruster heat needed to maintain the L2-type orbit. There are still unsolved complexities underlying the actual science case for Life Finder: *if* the goal is to detect the 7.6 μm methane feature — which is not definitively the relevant goal; see, for example discussions of the use of the 'vegetation signature' in Arnold et al. (2002) — the required collecting area accelerates from a plausible 220 m^2 (four or five 8-m telescopes) for a planet at 3.5 pc, to a mighty 4000 m^2 (eighty 8-m telescopes) even at only 15 pc. A new proposal to study Life Finder has recently been submitted to NASA by Shao, Traub, Danchi & Woolf (N. Woolf, private communication). Various reports on related studies can be found under NASA's Institute for Advanced Concepts (NIAC) www pages (http://www.niac.usra.edu/) including 'Very large optics for the study of Extra-Solar Terrestrial Planets' (N. Woolf); and 'A structureless extremely large yet very lightweight swarm array space telescope' (I. Bekey). The former includes an outline technology development plan for Life Finder, with costs simply stated as $\gg$\$2 billion.

Planet Imager: TPF aims to obtain images of planetary systems in which the planets appear as point sources. Resolving the surface of a planet is, at best, a far future goal requiring huge technology development that is not yet even in planning. Much longer baselines will be required, from tens to hundreds of km in extent. Formation flying of these systems will require technology development well beyond even the daunting technologies of Darwin/TPF – complex control systems, ranging and metrology, wavefront sensing, optical control and on-board computing. Having accepted that we are now peering into a much more distant and uncertain future, we can examine some of the ideas which are being discussed.

Life Finder studies (Woolf et al., 2001) have been used to evaluate the requirements for Planet Imager which, they consider, would require some 50–100 Life Finder telescopes used together in an interferometric array. Their conclusions were that *'the scientific benefit from this monstrously difficult task does not seem commensurate with the difficulty'*. This echoes the conclusions of Bender & Stebbins (1996) who undertook a partial design of a separated spacecraft interferometer which could achieve visible light images with 10×10 resolution elements across an Earth-like planet at 10 pc. This called for 15–25 telescopes of 10-m aperture, spread over 200 km baselines. Reaching 100×100 resolution elements would require 150–200 spacecraft distributed over 2000 km baselines, and an observation time of 10 years per planet. These authors noted that the resources they identified would dwarf those of the Apollo Program or the Space Station, concluding that it was *'difficult to see how such a program could be justified'*. The effects of planetary rotation on the time variability of the spectral features observed by an imager, complicates the imaging task although may be tractable, while more erratic time variability (climatic, cloud coverage, etc.) will greatly exacerbate any imaging attempts.

Hypertelescopes/OVLA:

Parallel to the Planet Imager studies, in Europe the LISE group (Laboratoire d'Interférométrie Stellaire et Exo-planétaire) carries out research in the area of high-resolution astronomical imaging, including imaging extra-solar planets. The group is studying several complementary projects for 'hypertelescopes' on Earth and in space (Riaud et al., 2002; Gillet et al., 2003). The steps needed to reach this goal are set out as requiring: (1) a hypertelescope on Earth – the OVLA (Optical Very Large Array); (2) a 100-m precursor geostationary version in space; (3) a km-scale version in a higher orbital location; (4) a 100 km version, including dozens of mirrors of typically 3 m aperture. Labeyrie et al. proposed the mission 'Epicurus', an extra-solar Earth imager, to ESA in 1999 in response to the F2/F3 call for mission proposals.

Their basic 'hypertelescope' design involves a dilute array of smaller apertures (an imaging interferometer) having a 'densified' exit pupil, meaning that the exit pupil has sub-pupils having a larger relative size than the corresponding sub-apertures in the entrance pupil (see Fig. 1 of Pedretti et al. (2000)). Their applicability extends to observing methods highly sensitive to the exit pupil shape, such as phase-mask coronography.

In the most recent published studies (Riaud et al., 2002) the hypertelescope is combined with such a coronograph to yield attenuations at levels of 10^{-8}. Simulations of 37 telescopes of 60 cm aperture distributed over a baseline of 80 m in the infrared, observing the 389 Hipparcos M5–F0 stars out to 25 pc (with simulated contributions from zodiacal and exo-zodiacal background) yields 10-hour snapshot images in which an Earth-like planet is potentially detectable around 73% of the stars. Gains of a factor 20–30 with respect to a simple Bracewell nulling interferometer are reported.

In space, the plans call for a flotilla of dozens or hundreds of small elements, deployed in the form of a large dilute mosaic mirror. Pointing is achievable by globally rotating the array, which is slowly steerable with small solar sails attached to each element. A 'moth-eye' version allows full sky coverage with fixed elements, using several moving focal stations (Labeyrie, 1999b,a). The geostationary precursor hypertelescope could be a version of TPF. An exo-Earth discoverer would require a 100–1000 m hypertelescope with coronograph, while an exo-Earth imager would require a 150 km hypertelescope with coronograph. In the approach of Labeyrie (1999b) a 30-min exposure using a hypertelescope comprising 150 3-m diameter mirrors in space with separations up to 150 km, would be sufficient to detect 'green' spots similar to the Earth's Amazon basin on a planet at 10 light-years, although these vegetation features are more prominent in the infrared (Arnold et al., 2002).

C ESO 1997 Working Group on Extra-Solar Planets

The ESO 1997 Working Group on the Detection of Extra-Solar Planets consisted of 16 members, and met on four occasions during 1996 and 1997. The assignment was to *'advise ESO [...] on how to help designing a competitive strategy in this field that is predicted to expand dramatically in the next years, and to become one of the leading fields of astronomy in the next century.'* The 1997 Working Group and its task were somewhat comparable to the current effort, with the notable difference that this time the Working Group was asked to provide recommendations to both ESA and ESO, thereby encompassing both space- and ground-based astronomy.

This appendix looks briefly at the findings and recommendations of their final report, published on 10 September 1997. This may provide some understanding of why some recommendations were successfully implemented while others were not, and what lessons can be learned from the past.

In the introduction of their report the 1997 Working Group states: *'Only by allocating a major fraction of time on some of its telescopes and developing new technology — and doing it now – will ESO fully exploit its potential in this field and be truly competitive.'* They then laid out their plan to achieve this goal. They identified six areas in which ESO could play a critical role, namely: radial velocity searches, narrow-angle astrometry, microlensing, direct detection, transits and timing of eclipses. The recommendations, planned timeframe, and status and achievements of each of these is summarised in Table 10.

Radial Velocity Searches: The main recommendation was to devote a major fraction of the observing time at the CAT and the 3.6 m to monitor the radial velocities of about 1000 stars over the next 5–10 years. They called for the development of a dedicated spectrograph providing an accuray of about 1 m/s. Such a survey was considered indispensable to provide targets for VLTI which was assumed to become operational by 2002. They also advocated high-fidelity calibration of the iodine cell for UVES and the timely development of CRIRES to provide a survey using twilight observations in order to obtain complimentary information in the IR.

Narrow-Angle Astrometry: The Working Group considered astrometry a very attractive method for the study of planets because it allows for determination of orbits and planet masses directly. It was considered complimentary to other search methods exploring different regions of parameter space. Achieving an accuracy of about 10 micro-arcsec was considered feasible. Realisation of the technique was regarded as technically very challenging, requiring knowledge of the length of the baseline to within 50 μm and the knowledge of the delay between the two stars with 5 nm precision over a 100 m baseline.

Microlensing: Microlensing was identified as a method which is in principle able to detect Earth-mass planets. Since searches for Jovian planets were already in the development phase in 1997 the Working Group suggested that ESO should focus on detecting Earth-mass planets. They suggested that a dedicated 2.5 m telescope should monitor the bulge with a large (1°) field detector (16k by 16k CCD) during a 120 night season. It would observe a few million uncrowded stars achieving 1 % photometric accuracy reaching $V = 20$ in a 4-minute exposure. A high sampling rate is crucial to obtain the characteristic of the short (5 hr) planet event on the microlensing light curve. No specific time frame was given but the Working Group called for an aggressive ESO-based campaign.

When VST/OmegaCam becomes operational in 2006, the technical capabilities for the above programme will be available. Microlensing searches for Earth-mass planets, though, are not part of the major science goals for VST/OmegaCam.

Direct Detection: Direct detection was considered essential for deriving many physical properties of extra-solar plants such as size, temperature, chemical composition etc. The Working Group stressed that it would be extremely challening to achieve the required contrast levels in particular from the ground. They identified a very powerful adaptive optics system as a key ingredient in combination with coronographic instrumentation and sophisticated data processing. They pointed out that spectroscopic signatures of planetary atmospheres should be detectable with high-resolution spectroscopy in the NIR (CRIRES) via their time-dependent Doppler shift. Other spectral features will be unique to the planet and therefore appear as 'alien' features in the stellar spectrum. They called for further studies of instrumental requirements, and an early realization of an instrument like CRIRES.

Transits and Timing Eclipses: The Working Group noted the potential of this method for detecting planets down to Uranus size, along with planets with rings and moons of giant planets. They mention the possibility of obtaining spectra of planets' atmospheres during transits. They also noted that timing of eclipses in binary stars was a simple method for detecting giant planets in these systems.

Table 10: ESO Working Group 1997: Recommendations and Outcome

Radial velocity searches		
Recommendation	Planned Timeframe	Status and Achievements
CORALIE survey at ca 5 m/s	start end of 1997	first light May 1998, 3 m/s, ongoing 200 nights/year
FEROS survey	end 1998	not done, FEROS moved to 2.2 m
Dedicated new spectrograph at 3.6 m	late 1999 at 1 m/s	HARPS: first light Feb 2003, operational at 1 m/s
UVES ready for RV studies	mid 1999	UVES first light, Sep 1999, iodine cell since 2000
CRIRES	mid 2000	first light late 2005
Narrow angle astrometry		
Recommendation	Planned Timeframe	Status and Achievements
Develop astrometric capability for VLTI	10 μarcsec by ca 2005	First AT installed Jan 2004
Astrometric program with auxiliary telescopes (AT)	asap, before ca 2002	ATs and PRIMA available by 2006
Substantial time on ATs for 10-15 years	start 2002	start 2006 ?
Design VLTI to achieve high astrometric precision	before procurement	done
Microlensing		
Recommendation	Planned Timeframe	Status and Achievements
Dedicate 120 nights on 2.5 m telescope on Paranal	not specified/Sep 2001	VLT Survey Telescope (VST) first light late 2005 ?
Develop 16k by 16k CCD	not specified/Sep 2001	OmegaCam, ready for shipment mid 2005
Develop new photometric data processing techniques	not specified	under development
Real-time follow-up	not specified	
Direct detection		
Recommendation	Planned Timeframe	Status and Achievements
High-order AO/coronograph at VLT	not specified	Planet Finder: phase A ended 2004
High-resolution IR spectroscopy CRIRES	mid 2000	first light late 2005
VLTI measurements	not specified	by 2006 ?
Transits and eclipse timing		
Recommendation	Planned Timeframe	Status and Achievements
1 m telescope/CCD	not specified	not implemented
100 deg^2 Schmidt telescope/CCD array	not specified	not implemented
1 m telescope with GPS clock	not specified	not implemented

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