The Search for Extrasolar Planets at ESO

FINAL REPORT OF THE ESO WORKING GROUP ON THE DETECTION OF EXTRASOLAR PLANETS[1]

Prepared by F. PARESCE and A. RENZINI

1. Introduction

A dedicated Working Group on this subject was created in 1996 and has since met four times. It is composed of the following members:

A. Hatzes (Texas), M. Kurster (ESO), A. Léger (Meudon), M. Mayor (Geneva), J.-M. Mariotti (Meudon), R. Mundt (MPIA), F. Paresce (ESO, chairman), A. Penny (Rutherford Appleton), D. Queloz (Geneva), A. Quirrenbach (MPE), A. Renzini (ESO), P. Sackett (Groningen), J. Schneider (Meudon), D. Tytler (San Diego), G. Wiedemann (ESO), H. Zinnecker (Potsdam).

The assignment of the WG was to advise ESO management and ESO committees 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.

ESO has great potential in the search for exoplanets. With the La Silla telescopes, the VLT, the VLTI, the special characteristics of the Paranal site, and the variety of professional expertise widely spread within the European astronomical community, ESO should be able to play a leading role in the search for exoplanets. For this to happen, however, a serious effort has to be made now to develop a global strategy and to allocate adequate resources. The WG recalls, in this context, that the substantial NASA contribution to the Keck telescopes and the Keck Interferometer is driven by its interest in the search for exoplanets. Some 40% of the time of one of the Keck telescopes will be dedicated to this scientific goal. Therefore, a sporadic, uncoordinated effort by ESO could hardly be competitive. 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.

In this report, the WG proposes a plan to do just this. We have identified where ESO can play a critical role and that, therefore require particular attention: radial-velocity searches, narrow-angle astrometry, microlensing, direct detection, transits and timing of eclipses. In the following paragraphs, we will present a high-level executive summary of the unanimous conclusions reached by the group and its recommendations to ESO for the proper exploitation of the opportunities in each one of these areas. The appendices (not included here) contain the detailed and quantitative justifications for these conclusions and recommendations.

2. Conclusions and Summary of Recommendations

2.1. Radial-Velocity Searches

The WG recommends that a major fraction of a spectroscopic telescope (successively the CAT and the 3.6-m or some combination thereof) be devoted to radial-velocity monitoring of $\sim$ 1000 nearby bright stars over the next 5–10 years. The availability of a very stable spectrograph (able to reach an accuracy of $\sim$ 1 m/s) would be particularly helpful, but still competitive results can be obtained even with the current instrumentation, provided adequate telescope time is allocated. A dedicated spectrograph could be developed either by ESO, or by a consortium of ESO institutes, provided an adequate fraction of telescope time will be reserved. The WG notes that such a radial-velocity survey is indispensable to prepare for VLTI astrometric observations. The search for exoplanets is currently listed as one of the primary scientific goals and drivers of the VLTI. Therefore, adequate target lists should be ready by the time the VLTI will start its operations in the year 2002. Such targets will have to include objects with confirmed radial-velocity variations, so that the VLTI narrow-angle-astrometry capability will allow to complete the determination of orbital parameters and planetary mass. The detection of Jupiter-like planets with either radial velocity or astrometric techniques requires several years of consecutive monitoring. Therefore, it is crucial to start an extensive observational campaign as soon as possible.

Specifically, the WG makes the following recommendations in this area

(a) The large survey to explore the domain of brown dwarfs and giant planets with an accuracy of 5–10 m/s at La Silla with CORALIE at the Swiss 1.20-m should be complemented and extended with FEROS at the 1.52-m telescope. The first should proceed as planned and with all due support from ESO and the second should be executed as soon as possible (see *The Messenger* No. 89, p.1). Together, these two instruments are in a position to make, in a rather optimum way, a southern survey of more than 1000 stars.

(b) A large survey to explore the domain of “normal” giant planets and, maybe, the domain of short period “Uranus”-type planets with an accuracy of 1 to 2 m/s should be started at La Silla as soon as possible. This will require the following substantial commitments:

– a significant fraction ($>$ 25%) of 3.6-m time over the long term (5–10 years)

– the construction of a dedicated, optimised instrument linked to the 3.6-m telescope that could be either the CES + VLC + cross-disperser together with a suitably large CCD (preferably 8K $\times$ 8K), if feasible, or a totally new spectrometer optimised to get the highest possible accuracy and fiber fed by the 3.6-m telescope. This instrument will be the most efficient one among all the possibilities offered by ESO.

(c) For this programme to be implemented quickly, therefore, in turn, also requires:

– an immediate study of the practical feasibility of a cross-disperser on the CES/VLC,

– a study and implementation of optical image slicers/scramblers and large CCD on the 3.6-m to CES link.

(d) The CAT should be kept operating at least until the time a major fraction of 3.6-m time ($>$ 25%) can be devoted to a high-precision RV survey. It should be completely dedicated to the goal of reaching the required RV precisions at ESO as quickly as possible. This implies equipping it with the upgraded CES + VLC + image slicers/scramblers and, for reasons of improved efficiency and stability, with its own fibre link from its prime focus to the CES + VLC. This will provide indispensable ancillary data in the form of line profile studies at R = 220,000 and precision RV work on a smaller sample of brighter stars. The CAT will then also serve as a most useful device for experimental tests of techniques to achieve the goal of 1–2 m/s precision (cross-disperser, SW, HW, etc.).

(e) Calibrate the Iodine cell of UVES and develop the specific software to allow extreme accuracy with UVES.

[1]A number of Appendices are attached to the complete Final Report. They are not published here.

(f) Develop CRIRES to provide complementary spectral diagnostics needed to confirm the planetary rather than stellar origin of the apparent RV variations and to augment the search for planets around IR-bright K and M stars. A planetary monitoring programme conducted with CRIRES could make extended use of twilight and early-morning time, since the typical target brightness will far exceed the sky background. The use of these times should be foreseen by VLT operations and scheduling.

Supporting documentation with greater detail on the above issues can be found in Appendices A and B.

Summarising, a schedule such as the following, then, would allow ESO to become competitive in this area with the rest of the world in the required time frame:

- end 1997: start of a short-term programme with CAT+CES+VLC+image slicers/scramblers
- end 1997: CORALIE survey begins; precision expected: 5 m/s
- mid-1998: CES + VLC +3.6-m + large CCD (without cross-disperser)
- end 1998: FEROS survey begins; precision expected: 5 m/s
- early 1999: start of the long-term survey with the CES + VLC + cross-disperser + large CCD + 3.6-m (if feasible)
- late 1999: start of the long-term survey with the 3.6-m + dedicated new spectrograph (if CES cross-disperser not feasible)
- mid-1999: UVES + VLT is available to start radial velocity searches of exoplanets
- mid-2000: CRIRES + VLT should be available to start complementary IR studies of exoplanet candidates.

2.2. Narrow Angle Astrometry with the VLTI

The VLT Interferometer has the potential to perform extremely precise narrow-angle astrometry (NAA). The atmospheric limit for determining the distance vector between two stars separated by 10″ in a half-hour integration is about 10 microarcsec. The technical realisation of this potential requires monitoring of the baseline vector with ∼ 50 micron precision, and measurement of the differential delay between the two stars with ∼ 5 nm precision over a 100-m baseline.

Astrometry with 10 microarcsec precision is capable of detecting the reflex motion of solar-type stars due to Jupiters at distances up to 1 kpc; gas giant cores, i.e. planetesimals with 10 Earth masses, could be detected around nearby stars. In contrast to radial-velocity measurements, astrometry allows a full determination of the planetary orbit, and, therefore, yields the planet mass directly (without any uncertainty due to the inclination of the orbit). Moreover, astrometry can be performed for any type of star independent of its spectrum. Therefore, two types of astrometric programmes can be envisaged: first, stars with planets known from radial-velocity surveys should be observed to determine the orbital inclination; second, an astrometric survey should be performed to look for planets around stars in those regions of the HR diagram that are not accessible to radial-velocity searches. The latter programme would include, for example, pre-main-sequence objects in nearby regions of low-mass star formation and in Orion.

It is also possible to perform astrometric measurements with sub-milliarcsecond precision using a single 8-m telescope (UT). An astrometric instrument based for example on the Ronchiruler technique would have widespread applications for determining parallaxes and proper motions of extremely faint objects; it could also be used to search for Jupiter-like planets around nearby stars. It might also be possible to use a “simple” CCD camera such as the VLT test camera for astrometric measurements with a precision sufficient to detect planets.

Specifically, the WG makes the following recommendations in this area:

(a) the VLTI should be designed from the beginning to have a NAA capability with the goal of reaching 10 microarcsec precision by ∼ 2005.

(b) the main astrometric programme of the VLTI should use the 1.8-m auxiliary telescopes (AT) only; it should start as soon as these telescopes become available and no later than ∼ 2002.

(c) a substantial fraction of the AT time should be made available for NAA for 10–15 years. In this way, a few hundred stars can be included in a long-term astrometric survey.

(d) the detailed design of the metrology system and focal plane instrumentation required for astrometric measurements with the VLTI should be started now and completed before the main elements of VLTI are procured.

(e) ESO should look favourably at suggestions to implement astrometric programmes on the UT’s but priority should be given to the astrometric mode of the VLTI.

2.3 Microlensing

A planet orbiting a microlens will create a distortion in the source’s light curve. If the planet is located in the lensing zone of its parent star, perturbed regions of high amplification will be generated. A background source passing (in projection) behind these regions will exhibit a short-lived deviation or anomaly in its microlensing light curve. The interest of microlensing as a technique for planet detection is the information contained in the light curve about the mass ratio and the projected orbital separation in units of the primary Einstein ring radius. Roughly speaking, because of the uncertainty on the Einstein ring radius of the primary which serves as a scaling factor, the mass of the planet and its orbital separation can be determined within a factor of three.

Provided finite source effects are not important, the probability of detection is a rather weak function of planetary mass ($\sim M_p^{-1/2}$) which makes the technique sensitive, in principle, to earth-mass planets. The reflex-motion methods discussed in Appendices B1 and B2 of this report can detect and characterise Jupiter- or Uranus-mass exoplanets but microlensing is the only one that is sensitive to earth masses and that can quickly detect Jupiters at larger orbital radii where they are actually found in our own Solar System. Due to the very low probability that a chance alignment occurs between the source and the lensing zone of a star ($(3–4) \times 10^{-6}$ toward the bulge of the Milky Way), many stars have to be simultaneously monitored to expect the detection of a few lensing events.

In practice, the source stars are in the bulge. To be observable, they must be bright and are, therefore, either red giants with $R^* = 13\ R_{SUN}$, or turn-off stars with $R^* = 3\ R_{SUN}$, the former being typically 3 magnitudes brighter than the latter. The lenses are random stars in the bulge or the disk. As microlensing is only weakly sensitive to the lens mass, the lens stars are most likely to be the most abundant ones, namely M stars of median mass of 0.2–0.3 $M_\odot$.

While the detection of Jupiter-mass exoplanets can be done against giants or turn-off stars, to avoid finite-source effects that dilute the signal, detection of earth-mass planets is more likely against turn-off sources. The former requires ∼ 5% accuracy photometry of giants with around-the-clock sampling at a rate of one point per ∼ 2 hours to get a correct characterisation of the event. This requires a set of longitudinally spread telescopes. The latter requires 0.5–1% accuracy photometry at a high sampling rate (e.g. one point each 20 minutes) but it can be done from a single observing site as the duration of the event is of the order of 5 hours. The unicity of the observation site decreases the probability of finding a planetary event by 1/3 but does not otherwise prevent a proper characterisation. However, an excellent-quality site is needed to obtain the accurate photometry routinely in the crowded bulge fields.

With the availability of one telescope at one site, the detection of terrestrial planets is possible, provided a 2.5-m-diameter-class telescope could be dedicated to the search for the duration of the bulge season (~ 120 nights). If equipped with a state-of-the-art, ultra-large-field-of-view, high-resolution imaging detector, it could conduct a microlensing search for turn-off source events and simultaneously monitor them. A 16K × 16K detector with a 1-square-degree field of view should yield 4×10^6 suitably uncrowded turn-off stars. With a good detector (50% total efficiency), quantum noise would give σ = 0.23% for a V = 20, R = 19 star, in 4-minute integrations. Current state-of-the-art image-subtraction techniques indicate that realistic photometry can be achieved at levels three times that set by the photon noise.

Thus, if systematics can be controlled, one might expect a 2.5-m telescope at Paranal to perform 1% photometry of V = 20 lensing turn-off sources in 5 minutes per field (4 minutes integration plus 1 minute overhead). Since sampling every 20 minutes is required, four fields could be continuously monitored. Fields of one degree on a side are large enough that the search for microlensing events could be performed simultaneously with monitoring, with no additional observing time. About 250 stellar microlensing events (with maximum magnification above 1.13) could be expected in such a scheme over a 120-day bulge season. In principle, real-time alerting capability would not actually be required, but the auxiliary rewards of real-time detection (such as to allow follow-up spectroscopy with a very large aperture) are great. With this many events being monitored this precisely and frequently, the resulting 1.5% sensitivity to earth-mass detection could lead to about 4 earth-mass planets per season, if every lens has a terrestrial planet in its lensing zone.

Supporting documentation with greater detail on the above issues can be found in Appendix C of the complete Final Report.

Specifically, the WG makes the following recommendations in this area:

(a) Since experiments specifically designed for Jovian-mass planets are already underway and since other techniques can detect and characterise such planets, we do not recommend that ESO make a major effort with this aim using the microlensing technique. The possibility for a large single step forward lies in the detection of terrestrial-mass planets, an area in which an aggressive ESO-based campaign could result in a breakthrough.

(b) The best way to implement such a campaign is to dedicate 120 nights during the bulge season of a 2.5-m-class telescope on Paranal to a search for terrestrial planets. Since image quality is crucial in crowded southern fields, ESO will be in a unique position by having the best site in the world to study the bulge.

(c) Develop a 16K × 16K camera to allow both alerts and follow-up.

(d) With a few HST images of bulge fields, make extensive simulations of (i) planetary lensings and (ii) photometric measurements in crowded fields in typical Paranal observing conditions.

(e) Develop new data-processing techniques to control the photometric systematics resulting from crowding and seeing.

(f) Develop a data-processing system able to extract stellar lensings in a day and planetary ones in real time ($<$ 15 minutes) in the monitored stellar events. This would allow the VLT to be used to obtain simultaneous spectra throughout the event.

(g) Automate the observing programme and reduction process so that eventually on-site personnel costs can be kept to a minimum.

(h) The European survey group, EROS II, operating from La Silla, is expected to provide the largest number of giant alerts. Supporting their effort appears highly desirable, the more so as it will increase the European expertise in the domain – a needed capability to prepare for the future.

(i) If the expected real-time alert capability of the follow-up teams, like PLANET and GMAN, is fully realised, flexible ESO scheduling and target-of-opportunity status on the 3.6-m would be highly desirable. This would allow spectra of the event to be taken throughout the short-lived anomaly; comparison baseline spectra could then follow at a later time. Such spectroscopy would provide detections or limits on the mass of the primary lens (i.e. the parent star of the planet) by looking for evidence of a second stellar spectrum, at a different radial velocity, superimposed on that of the source star.

2.4. Direct Detection

Direct detection of photons originating from extrasolar planets gives crucial information on these bodies that cannot be obtained with indirect methods. With direct spectroscopic and photometric observations it is, in principle, possible to determine size, temperature, chemical composition, atmospheric stratification, rotation rate, and the presence of surface features. Because of the faintness of extrasolar planets, and because of the large contrast between planet and parent star, such observations are extremely challenging. For example, it might be possible, from the ground, to observe objects like 51PegB in the near-IR, and perhaps "warm Jupiters" (i.e. planets the size of Jupiter, but with T $>$ 300 K) in the mid-IR.

Several methods have been proposed to carry out such studies, either with the VLT Unit Telescopes instrumentation, or with the VLTI:

(1) In the visible and the near-IR, the VLT UT's are able to angularly resolve a star from its planetary system up to distances of several tens of parsecs. The problem lies in the tremendous contrast between the images of the planets and their parent star. In theory, it can be overcome, but this requires a high-order AO system associated with a high efficiency coronograph and post-processing with the dark speckle method. Although future large space telescopes will be at an advantage for this kind of direct imaging, this method does not require heavy instrumental development and should be tried with the VLT, especially if photon-counting detectors become available in the near IR.

(2) Planetary spectral features predicted by recent atmospheric models should be detectable with high-resolution infrared spectroscopy using CRIRES. The planetary signal will be uniquely distinguished from the superimposed stellar spectrum because of the large Doppler shift due to the orbital motion of the planet. The infrared between 1 and 5 microns offers a vastly reduced contrast of planetary signal to stellar (noise) flux. A spectroscopic detection, in particular, of features known not to exist in stellar spectra, would be direct and unambiguous.

The spectroscopy can be supplemented by low-resolution spectro-photometry targeting the apparent infrared brightness variation (phases) of a tidally locked, isolated close planet. The instrumental requirements have been studied and incorporated in the CRIRES conceptual design. The spectro-photometry mode is available simultaneously in the low-resolution predisperser. The early realisation of this high-resolution echelle spectrograph, and its extended operation during twilight and early morning time are highly desirable. More details on this method can be found in Appendix D of the complete Final Report.

(3) If the VLT Interferometer is equipped with spatial wavefront filters such as single-mode optical fibres, the fringe amplitude can be measured with great precision. This can be used to make measurements of "double stars" with large magnitude difference, such as star-planet systems.

(4) Gaseous planets have strong molecular absorption bands. Within the bands, the planet is dark, and the photocentre of the star-planet system is centred on the star itself. Outside the bands, the photocentre is shifted slightly towards the planet. This shift of the photocentre might be detectable as a wavelength-dependent phase shift with the VLTI.

The working group therefore recommends that the instrumental requirements for direct planet detection be studied, and that appropriate instruments be included in the instrumentation plans for the VLT and VLTI. Specifically, the early realisation of a high spectral resolution IR spectrograph like CRIRES would be highly desirable.

2.5 Transits and Timing of Eclipses

Transits of extrasolar planets can be detected from the ground down to Uranus sizes. This method has, in addition, the very unique capability of detecting Saturn-like rings and, by timing of transits, habitable earth-mass moons of giant planets. The detection of transits constitutes also a first step toward the subsequent spectroscopic investigation of giant planets' atmospheres during transits. The timing of eclipses of close eclipsing binaries is a simple method for the detection of giant planets around binary stars. Possible practical implementation strategies are described in detail in Appendix E.

Specifically, the WG makes the following recommendations in this area:

(a) For the profile and timing of giant planet transits, two options are available: dedicate a 1-m telescope equipped with a CCD camera full time to the search or partially dedicate a 100 deg^2 Schmidt telescope equipped with a CCD array.

(b) For the timing of eclipsing binaries, partially dedicate a 0.8–1-m telescope coupled to a GPS clock.

3. Human and Capital Resources

The availability of adequate resources is indispensable for the successful completion of a vast and diversified effort as the one envisaged in this document. These necessarily include human as well as capital resources.

As far as human resources are concerned, it has to be realised that all the projects listed in the previous section will take many years to be completed (typically more than five years). Strong commitment by dedicated teams is therefore a prime necessary condition for any of such programmes to get started, conducted and completed. To some extent, ESO can facilitate the formation of teams with such strong commitment, but the initiative has to come directly from the community.

The search for exoplanets is a novel branch of astronomy, yet, if one looks in detail to what this search will consist of, one sees that the observational techniques will basically reduce to just a few ones. Specifically, to stellar high-resolution spectroscopy, stellar photometry in crowded fields, stellar high-accuracy photometry, and stellar narrow-angle astrometry. Expertise in these fields is widely spread within the ESO community. Therefore, recruiting the necessary human resources should not be a problem. Instead, the blooming of this new branch of astronomy clearly offers a unique opportunity to many ESO astronomers, and especially to the younger ones, to relocate themselves towards a new scientific frontier while taking full advantage of their own experience and technical know-how.

As far as capital resources are concerned, these come in two categories: telescopes and instruments. With the exception of the microlensing experiment, the other projects do not need new telescopes, but major fractions of the time of existing telescopes. In the case of the CAT, however, the dedication of this telescope to the radial velocity project requires to maintain the telescope in operation for many years, while current plans foresee its decommissioning by the end of 1998. New instruments, such as the high-resolution spectrograph capable of reaching 1 m/s accuracy and the one square degree CCD camera, are not in the current ESO planning. It is difficult to see how ESO could find the necessary resources out of its present budget, at a time when ESO is already so deeply engaged in completing the VLT/VLTI. Therefore, the allocation of fresh capital resources is likely to be critical for ESO to play the leading role in the search for exoplanets that is made possible by its vast complement of telescopes and by the scientific composition of its community.

The most promising way of proceeding appears to be one in which the scientific teams themselves provide at least part of the capital investments, or provide for the operation of a telescope. This will also make easier to the OPC to allocate them the extended periods of observing time that are necessary for each of the projects. Indeed, such an investment would represent a concrete embodiment of the long-term commitment that will have to be demonstrated before such long-term projects could be approved.

Latest News: The First VLT 8.2-m Zerodur Mirror Has Arrived at Paranal

On Tuesday, December 9, 1997, the first of the VLT M1 mirrors arrived on Paranal after a 3-day journey from Antofagasta.