Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005, pp. 359-367

Scientific Requirements on Space Interferometers

M. Fridlund [1], R. den Hartog[1], A. Karlsson[1]

[1]RSSD, ESTEC, Noordwijk, The Netherlands

Abstract: In the context of the European Space Agency's new science implementation plan - Cosmic Vision 2015-2025, the search for Terrestrial Exoplanets forms a major part of one of the major themes. For a number of years, both ESA and NASA have been studying different technologies in order to design space missions that can search for and study the physical parameters of planets like our own, orbiting other stars. The ESA Darwin study is arguably the one in world which has progressed the furthest. This is probably the most ambitious space mission contemplated so far, but will result in a complete survey of single stars within a distance of 25pc. In this paper we present the context of the mission as well as the scientific case - both at top level and the detailed case which is broken down for actual implementation.

1 Introduction

Darwin is the European Space Agency's mission to study other worlds like our Earth and determine their habitability. In ESA's Cosmic Vision Science plan for the period 2015 - 2025, a number of themes have been identified. These themes contain a number of elements all centered around a fundamental question that currently remain open for mankind and the answer of which would have great scientific and social impact on our understanding of the Universe. Theme 1 in this context is answering the question: "What are the conditions for life and planetary formation?". This is subdivided into the following three topics:

1. From gas and dust to stars and planet
2. From exo-planets to biomarkers
3. Life and habitability in the Solar system

Addressing these subtopics, will allow us to place the Earth and the Solar System into the proper context of planetary formation and evolution, leading to the new science of Comparative Planetology. Comparative Planetology in this context means the active comparison between different solar systems, of different origin, age, evolutionary history, etc. This will allow true comparisons and make it possible to draw conclusions on how different circumstances lead to different evolutionary scenarios. The ultimate element is of course life as we know it. The study of its origin and evolution would lead to a formidable change in our understanding of ourselves. In contrast, the term Comparative Planetology is sometimes used to refer to comparisons between bodies in our own Solar System. Here one is truly comparing Apples with Pears, since it is clear that what one is working with is the result of the different circumstances occurring in different places in the original solar nebula on the planetesimals formed at that time. This does not mean that one can not make meaningful comparisons. As an example one can discuss Venus and the Earth, which are located relatively nearby each other in the Solar System (both orbiting within the currently Habitable Zone). They are of the same size, and with roughly the same average density. Nevertheless, they are completely different in appearance, with no really good understanding so far of why this is so. The Comparative Planetology on which we are currently embarking will allow such questions to be addressed in a statistical way. If we want to arrive at this level of understanding, it will be required to build new scientific instruments, probably in space. In order to define what kind of instruments we want to have we must define the scientific questions that we want to answer, and a t what level. In the context of Theme 1, these can be defined such:

1. What is the uniqueness of our own Earth?
    - The searching for and study of Terrestrial exoplanets
    - The study and characterization of such planets and their atmospheres
2. Are we (lifeforms) alone?
    - The habitability of these worlds
    - The search for biomarkers
3. What is our past and future?
    - The formation of planets of different kinds
    - The evolution of planets

2 Specific Scientific Case

The primary scientific case must contend with two possibilities:

- Terrestrial planets are common through the Universe or at least in our neighborhood
- Terrestrial planets are extremely rare or even non-existent

Given these two cases it is clear that a search for TE's in any sample of stars must be performed in such a large sample that even a negative result is meaningful. The primary scientific case can be defined thus:

To search for, and study Earth-like planets in the habitable zone around Solar type stars in a large enough (150 to ¿ 500) sample, to be statistically significant.

There are several comments to make. First, What is a solar type star? If we really want to be specific, it is a G2 main sequence star of roughly 4.5Gyrs of age. If we then want to search the sample specified above, i.e. several hundred objects, the search radius has to be extended to several hundred parsecs or more. In order to have a statistically significant sample of single stars, within say 25pc radius we need to include all F, G, K and some M dwarfs that are currently known. We will discuss this sample in the next section. Secondly, these stars are even within their specific types going to be vastly different depending on differences in age, metallicities, activity, conditions for habitability, and other physical properties. Thirdly, the definition and existence of the so-called habitable zone is going to be a function of the stellar properties. In the following sections we will also discuss these aspects in detail. To study any terrestrial planet found, it will be necessary to analyze the planetary light in detail. The first step is obviously to detect the planet more than once. Apart from confirming the existence of the object, this allows a determination of its orbit and under certain assumptions about the albedo, its mass. An analysis of the planetary light will permit us to estimate this albedo, its temperature and if it has an atmosphere, and what the composition of the latter is. All of this is with restrictions and to a greater or lesser level going to be model dependent. The habitability of any discovered body will depend on these parameters, but the most exciting aspect is that it is in principle possible to determine if life exist on terrestrial exoplanets if they are close enough. This depends on the existence of so-called biomarkers. Life - at least as we understand it - modifies its surroundings. All life on the Earth exists more or less out of equilibrium with the rest of our planet. The most obvious cases are due to Oxygen today and Methane in the earliest phase of the history of life. Note that we are discussing chemical equilibrium here. As an example one can mention that if all life was somehow removed from the Earth, essentially all Oxygen would be removed from our atmosphere in the relatively short time of 4 million years. It would be converted into Carbonates, Silicates and Ferro-oxides (rust), plus Water. Signature of these biomarkers can be found in many parts of the electromagnetic spectrum. As can be seen from Figure 1, there are a number of relevant lines in the infrared region between 6.5μm and 20μm. What is also very clear is that the spectral characteristics of the three terrestrial planets in our solarsystem, Venus, the Earth and Mars are very different. The signatures of the Earth immediately singles it out as a planet with water and ozone, the latter which implies abundant molecular oxygen. There are also important biomarkers in the visual wavelngth range. Here, however, much higher spectral resolution will be needed in order to correctly interpret data.

2.1 The main requirements

The main requirements for a mission fully achieving the objectives for the Theme 1 in the Cosmic Vision plan are summarised in Table 1:

3 Technology

If we want to search for Earth-like planets with space based assets, we have essentially two ways to go depending on the choice of wavelength. The two ways are nulling interferometry in the IR and Coronography in the visual λ-ranges, respectively. The systems then have to be traded against each other in technical difficulty, complexity, cost and timeliness (technical readiness).

Nulling interferometry utilizes the destructive fringes in an interferometer with appropriate phase delays to put the central object (the star) on and thus cause its light to diminish with a factor of 5 or 6 orders of magnitude. The interferometer need to be a free-flyer in order to fulfill its potential. This means that it can expand the baseline as one is observing progressivley more distant objects, and as long as the integration times does not become prohibetively long, the search space will be very large. This means that an interferometer is open ended and provides enough flexibility for an extended mission. The operation in the 6.5μm to 20μm band allows to relax the optical requirements, and a relatively low spectral resolution of ≈ 20 will deliver the full science for more than 150 targets in a reasonable time (2 years of detection and 3 years of spectroscopy). The telescopes need to be of 1-4m class depending on the full mission size, and the number of telescopes in the array. If sub-interferometer modulation is

	Specification	Comment
Stellar Types	F, G, K and M type stars	Solar type stars defined as F5 to K9
Stellar distance	< 25pc	Extended mission to > 30pc
Number of stars surveyed in 2 years	> 150	Negative result must be meaningful
Planet radius	1 R_{Earth}	Extended mission detect planet with 1/2 Earth surface
Spectral range	6.5μm – 20μm	Covers key absorption lines
Spectral resolution	> 20	H_2O, O_3, CO_2, CH_4
Acceptable level of exo-zodi	10	Max in special cases 30 exo-zodi
Number of revisits of detected planets	> 3	Orbit determination
	Derived requirements	Comment
Detection phase	2 years	Search of > 150 stars
Spectroscopy phase	3 years	Requirement is > 15 systems analysed spectroscopically

Table 1: Main Requirements of the mission. In some cases objectives for an extended (longer than 5 years) mission are shown

going to be implemented, one need at least 3 telescopes, providing a transmission pattern on the sky that allow easier interpretaion. In principle it is possible to operate a simple Bracewell interferometer (consisting of only 2 telescopes), and modulate by rotating the interferometer.

The coronograph on the other hand, need to operate in the visual (0.5μm to 1.06μm) if it is not going to be impossibly large. Nevertheless, it can not be small. The TPF-C has been suggested to have a mirror of 8m $\times$ 3.5m (assymetric in order to improve the coronography). Further, the wavefronts need to be of the order of 0.03Årms. The spectral resolution need to be at least 70-150 for the relevant lines. The problem is that even such an instrument can search only the closest 30 of the solar type stars completely. A less complete survey/study can be carried out around another 50-100 objects. The coronograph is not open ended. You can only search the designated space and if the prevalence of Earth-like planets is poor in the immediate vicinity of the Sun, the search can not be extended. Further, it leaves no heritage since it is not likely that very large monolithic telescopes will be constructed in space anytime soon.

As a consequence of these deliberations, as well as its commitment to eventually develop space interferometry (a so-called "green dream" already in the Horizon 2000 plan of ESA - see Bonnet, 1990), the European Space Agency has selected infrared interferometry between 6.5μm and 20 μm as its baseline technology for the search for and study of Terrestrial Exoplanets. The Darwin study, which has been in development since 1997 have evolved significantly during this time. Originally based on 6 telescopes each of 1.5m diameter, and each on its own free flying satellite, together with a beam combination satellite (a free flying optical bench) and a communication satellite, the design has been significantly simplified. In conjunction with a significant technology development program, this has resulted in a credible baseline mission design currently being studied by European industry. The baseline mission today consist of 3 telescopes of more then 3m (up to 4m) diameter. The mirrors are based on Herschel mirror technology polished to normal (rms surface accuracy of 1/10 wave at 500nm) optical quality. The reason for abondaning the 6 telescope array which produces a central null with a shape proportional to θ^4, where θ is the angle of the optical axis, and implementing a 3 telescope configuration which has a central null that is much narrower, proportional to θ^2, was the realisation that a wider null was important only in a small number of the very closest stars (Kaltenegger, 2004; Kaltenegger et al., 2005). A significant simplification in cost and complexity could thus be achieved at the price of abandoning (or increasing the integration time for) a very small number of targets. Three different arrangements are baselined - the triangular and the linear Three Telescope Nullers (TTN's) respectively (see Figure 2 & 3). These configurations, together with a third, designated EMMA, and consisting of 3 very slow mirrors flying on the surface of a parabola, and with the beamcombiner deployed $\approx$ 1000m away, are currently being studied under two industrial contracts. The advantages of the EMMA configuration include greater skyaccess (95%) and that shorter baselines are possible. Further, the focal length is constant and the long propagetion of the wavefronts lead to small errors to be corrected in the beam combiner. The telescopes are essentially replaced by reflectors, and the transfer optics can be excluded. The metrology is simpler with an out-of-plane reference. The thermal shielding becomes simpler with respect to the Sun, but baffling against straylight may be a problem. These studies, the first phase of which is expected to last until September 2006, are to be considered assessment studies. They are reflecting the maturity of the technology program that has been carried out in Europe between 2000 and now. A technology plan for the further development of Darwin is being developed in the context of the Cosmic Vision plan. Apart from the nulling interferometry technology, another key element is the formation flying. Although the precision required is of order cm (while the rest of the optical delay is corrected in the beamcombiner with delay lines of the same order), the number of spacecraft and the six degrees of freedom needed makes this a critical technology. Currently, it is planned to develop a testbed on the ground. Further, a Darwin precursor free-flying space experiment with 2 spacecraft is being developed by Sweden in partnership with France and Germany for a launch in 2008. It utilizes technology developed in ESA's technology researc program specifically for Darwin. Mission analysis for alternatives with both one (Ariane 5) and two launchers (Soyuz-Fregat) have been carried out for the L2 (Earth-Sun Lagrangian) alternative.

4 Imaging astrophysics with the nulling interferometer

A nulling interferometer does not measure visibilities as a 'normal' Michelson interferometer. Instead, the primary beam of each telescope, is transmitted, with appropriate phase delays, to the beam combiner where the central part is 'nulled out', leaving an amplitude to be detected. Depending of the number of telescopes and the geometrical arrangement, and including internal ('chopping') and external (e.g rotation of array) modulation, this translates into a transmission pattern on the sky (Figure 4). It is clear that when searching for and study planets, this transmission pattern can be tailored to the appropriate search space. It is equally clear, that this can be used also for imaging astrophysics. Assuming, e.g. that one is observing a starforming protoplanetary disk or the inner part of an Active Galactic Nuclei, it will be possible to create an image with a spatial resolution of order 1 milliarcsecond between 6 and 20 μm. The spectroscopy that can be carried out of the (relatively compared to the μJy planetary sources) bright objects can be hinted at in ten recent MIDI results (Nature article)

5 Simulation of Darwin performance

An analytic simulator of the complete Darwin system has been developed at ESTEC. It uses modules to calculate each element in the interferometric observation as a function of time and

Stellar type	10pc	20pc	30pc
G2V	18h (33h)	28h (54h)	109h (173h)
G5V	12h (22h)	27h (46h)	105h (166h)
K2V	4h (9h)	26h (37h)	104h (157h)
K5V	3.7h (6h)	26h (35.5h)	249h (155h)

Table 2: The values are for 3 observations of one Earth in the Habitable Zone with a signal to noise of 5. One spectrum (in paranthesis) with ignal to noise of 7 in the faintest part of the continuum of each system

wavelength, resulting in a signal-to-noise for each object. In order to simulate a complete mission we make the following assumptions:

1. Scenario 1: 1 Exo-zodi (= to level of Solar System or less). Observation of 500 F, G, K and M star systems out to 25pc – 30pc. Four band colours defuining continuum and CO_2, and O_3. Spectroscopy with a resolution of > 20 for 50 systems or more during a 10 year mission.

2. Scenario 2: Likewise for at least 150 systems with 10 Exo-zodi in a 5 year mission.

As input, the target star catalogue of Eiroa et al. (2003), Kaltenegger et al. (2005) has been used. More sophisticated software is under development at ESTEC and in European industry.

As examples of the results we can inspect the following table: The Darwin prime target list contain a total of 607 F, G, K and M dwarfs, excluding multiple objects. Of these we find 42 F stars, 93 G, 232 K and 240 M stars out to 25pc. It is understood that:

- The list is incomplete as what concerns K and M stars.

- The GAIA mission of ESA (launch 2012) will after 1.5 years complete the catalogue out to 25 pc for all stellar types down an apparent R-band magnitude of 22.

The red dwarf stars are not considered solar type as such being significantly less luminous than the Sun. Nevertheless, they are energy sources and we already know several cases where nearby red dwarfs have been found to be the primaries in planetary systems of the Pegasid type (e.g. GJ 436, G1 581 and Gliese 876). It can threfore not be excluded a priori that they are hosts to Earth-like planets. An interesting aspect is that the Habitable Zone is located at such a distance from an M-dwarf that any planet will have bound rotation. This does not mean that they will not be able to host life of some kind, since it has been shown that mixing in the atmosphere could lead to habitable temperatures. Further, their mainsequence life time is extremely long. The influence of the increased activity (most M-dwarfs are flare stars) is currently unknown, but may be actually be beneficient to the development of complex life (through a higher rate of mutations). There is therfore ample reason to include these objects in the Darwin target list (also because they are extremely numerous). In conclusion one may state, that there are about 1000 single stars available for Darwin out to a distance from the Soalr System of 30pc. More than half of these are going to be late K and M dwarfs with significant longer lifetimes than our Sun. As what concerns exact solar analogues there are less than 100 out to 25pc.

6 Darwin – Scenario for implementation

ESA and the advisory structure (Terrestrial Exoplanet Science Advisory Team, TE-SAT) have started to sketch how a mission like Darwin could be implemented. The instruments are essentially integrated into the telescope(s)/beamcombiner/space craft and as such will be developed and built by ESA. The scientific community will be involved in the mission in a fashion very similar to that used in the HIPPARCOS mission (and to be used for GAIA). It is therefor expected to form a number of scientific consortia who will help in the development of the mission, the preparatory observations (extremely intensive), the preparation and selection of the target stars and their individual priority, the development of interpretative methods and software, etc. Further the international aspect has to be taken into account. Darwin is currently being developed in parallell with the NASA Terrestrial Planet Finder (TPF). A letter of agreement between ESA and NASA calls for a close scientific collaboration, including having joint members on science teams, exchange of non-propritary information and joint Darwin-TPF conferences. The stated aim is towards a joint mission although at the time of writing no such decision has been made. Nevertheless, it is likely that a form of collaboration on the mission will take place.

7 The heritage of Darwin

It has been clear for a long time, that eventually new instruments simultaneously providing both high sensitivity and extremely high spatial resolution particularly in the (far-) Infrared. This is also true at shorter wavelengths, and the ultimate goal will be to produce resolved images of the surface of exoplanets, as well as study phenomena that we now only can study at relatively short distances in other galaxies. Monolotic telescopes and coronographs can only be built just so big, and noting that e.g. The proposed 100m ground based Extremely Large telescopes can not perform at the level of the proposed Darwin, much less carry out these very ambitious goals. Very large (space based) interferometers will have to be built. As examples the hypertelescopes, developed by Labeyrie and coworkers, can be mentioned. The projects that already are being sketched on are e.g. The Terrestrial Planet Imager and the Life Finder. Large FIR interferometers can reach significantly better than 1 μJy in less than one hour of integration. Visual hypertelescopes can create an image of the Earth at 20 pc with 50 resolution elements across the surface.

8 Conclusions

The Darwin study has matured significantly in the last few years, mainly as a result of extensive scientific studies and a through technology development program. As a consequence Darwin is a serious contender for implementation in the next Space Science Program of the European Space Agency. Building on the highly succesful Horizon 2000 and 2000+ programs, the Cosmic Vision 2015-2025 program has as one of its major themes the understanding of our own place in the Cosmos. Darwin, or a variation of it will very likely be the first element in the continuing quest for understanding this 'Big Question'.

Acknowledgements

I acknowledge the contributions and valuable discussions with the ESA Darwin team and the Terrestrial Exoplanets Science Advisory Team. The studies relevant to Darwin are carried out in parallell with the NASA studies for the Terrestrial Planet Finder. Under a Letter of Agreement, discussions are continuously being carried out between the European and NASA communities.

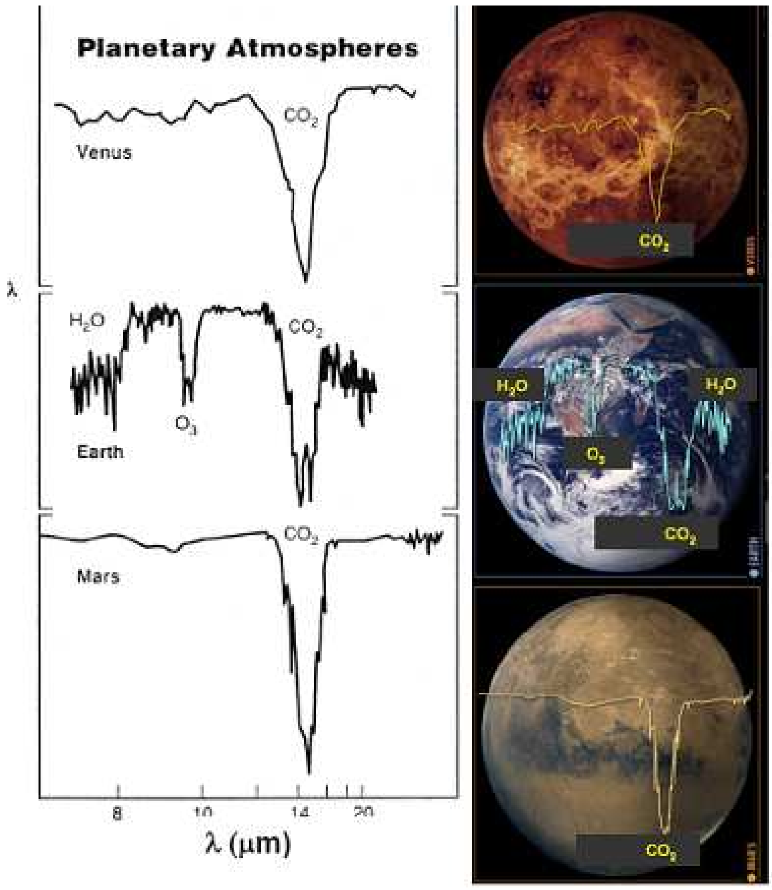

Figure 1: Spectra of the three Earth like planets in the solar system. The Earth immediately stands out with its clear signatures of H_2O and O_3. It has been concluded (e.g. Owen, 1980) that the latter species is caused by life and indicates an atmosphere out of chemical equilibrium. Note that based on this criteria we can already now conclude that there is no life (as we know it) on Mars.

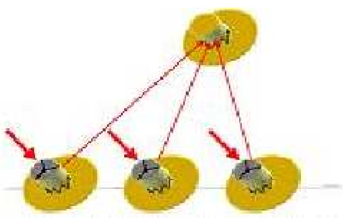

Figure 2: The Linear Triangular Telescope Nuller. One of the baseline concepts currently being studied in detail in Europe

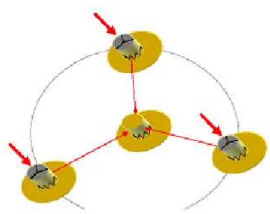

Figure 3: The Triangular Telescope Nuller. This configuration has the beamcombiner in the center and have relaxed requirements on the beam combination

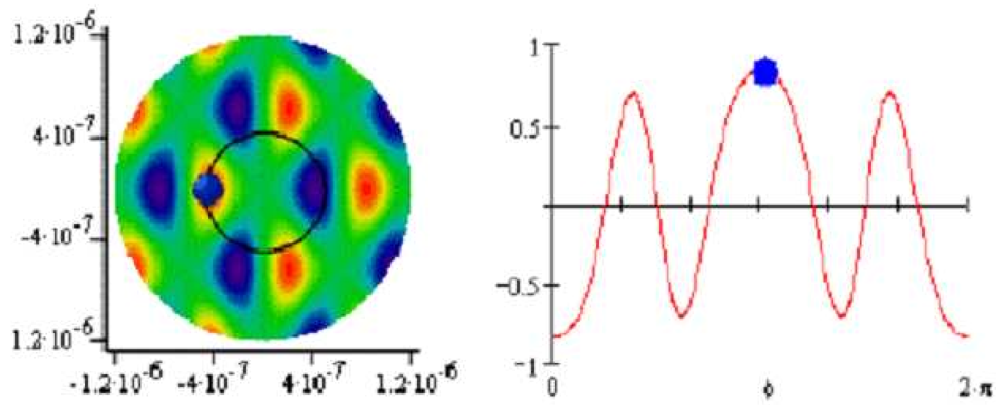

Figure 4: Transmission pattern (instanteaneous and with rotation) of a TTN array demonstrating the transmission pattern of the interferometer on the sky. Rotation modulates the signal and allow the interpretation of complex morphologies

References

Bonnet, R.M., 1990, "ESA's 'Horizon 2000' Programme", Evolution in Astrophysics : IUE Astronomy in the Era of New Space Missions ; proceedings of an international conference held in Toulouse, France 29 May - 1 June 1990. Organised by European Space Agency, National Aeronautics and Space Administration, Science and Engineering Research Council, Centre National d'Etudes Spatiales; co-sponsored by Universite Paul Sabatier. Edited by E.J. Rolfe. Paris, France : European Space Agency ; Noordwijk, Netherlands :ESA Publications Division, ESA SP-310, 1990., p.167

Eiroa, C., Fridlund, M., Kaltenegger, L., 2003, In: Proceedings of the Conference on Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets, 22-25 April 2003, Heidelberg, Germany. Edited by M. Fridlund, T. Henning, compiled by H. Lacoste. ESA SP-539, Noordwijk, Netherlands: ESA Publications Division, ISBN 92-9092-849-2, 2003, p. 403 - 407

Kaltenegger, L., 2004, Search for Extraterrestrial Planets: The DARWIN mission. Target stars and Array Architectures, PhD Thesis, Karl Franzens Univeristy, Graz, Austria

Kaltenegger, L., Fridlund, M., Karlsson, A., 2005, "Requirements on the stellar rejection on Nulling Space Interferometers", Astrophysics & Space Sciences, submitted

Owen, T., 1980, The Search for Early Forms of Life in Other Planetary Systems - Future Possibilities Afforded by Spectroscopic Techniques, STRAT. SEARCH LIFE/UNIVERSE - MONTREAL - AUG1980 P.177