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The Darwin Mission

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Abstract. The InfraRed Space Interferometer Darwin is an integral part of ESA's Cosmic Vision 2020 plan, intended for a launch towards the middle of the next decade. It has been the subject of a feasibility study and is now undergoing technological development. The scientific scope is aimed towards developing a system that could carry out the search for, and characterization of, Earth-like planets orbiting other stars. A secondary objective is to carry out imaging of astrophysical objects with unprecedented spatial resolution. The implementation of Darwin is based on the new technique of nulling interferometry in the mid-IR, and becomes the culmination of a decade of technology and science precursor missions. Darwin is also foreseen to be carried out in an international context.

1. Introduction

The Infra Red Space Interferometer Darwin (IRSI-Darwin) is a major element in the Cosmic Vision 2020 program of the European Space Agency. Darwin has the explicit purpose of detecting other Earth-like worlds, analyze their characteristics, determine the composition of their atmospheres, and investigate their capability to sustain life as we know it. As a secondary objective, it will also provide interferometric imaging of astrophysical objects in the wavelength range of the thermal infrared (IR) with unprecedented resolution. This latter goal will, however, not be described further in this paper.

The closing years of the 20th century have allowed us, for the first time, to seriously discuss interferometric instruments deployed in space. With the express purpose of achieving unprecedented spatial resolution, these missions will lead to new astrophysics. Especially - and this is the greatest challenge - we expect to be able to carry out the first detailed survey for nearby terrestrial exoplanets. We define those as planets similar to our own Earth as what concerns size, mass and orbit whilst orbiting other stars than our sun. The detection and study of Earth-like exoplanets promises to usher in a new era in science and will affect a broad spectrum of science and technology. We can now confidently expect the first results from space-based interferometers within 10 years. Sophisticated results will follow in short order.

The European Space Agency (ESA) identified interferometry from space as an important topic already in the original Horizon 2000 plan in the early eighties. In this scheme, it was classified as a "green dream:" a topic considered to be worthy to pursue scientifically but still technologically immature, and thus a candidate for the future stages of European space exploration. In this context, a number of conferences and workshops were held during the rest of the 1980's, the purposes of which were to explore and define the scientific cases in preparation for the next generation of missions. Although the general topic of high-resolution imaging was considered as the overall scientific driver for developing an interferometric capability in space, the search for terrestrial exoplanets did figure prominently already in this beginning phase. When, in the beginning of the 1990's, an external survey committee made its recommendations for the extension of the Horizon 2000 program (H2000+), they responded to technology developments worldwide, by identifying interferometry from space as a cornerstone candidate for the new program. Within the context of interferometry, three topics were identified for further study:

- Astrometry
- The search for terrestrial exoplanets, including the characterization of their properties and atmospheres and the possible detection of biospheres through remote sensing
- Astrophysical imaging at a spatial resolution 1 - 2 orders of magnitude better than that foreseen to be achievable with the Next Generation Space Telescope. This would lead to light being shed on topics as varied as the formation of stars and planetary systems and the observation of galaxies at very high redshift.

Of these topics, the first was considered to be (relatively) simpler in implementation, and resulted in the GAIA proposal to ESA and a pre-phase A study carried out by ESA's science directorate resulted in GAIA not any longer being an interferometric mission.

The Infra Red Space Interferometer Darwin was studied by ESA, at system level, between 1997 and 2000. The study, carried out by Alcatel space division in Cannes, France, was thus focused on developing a system that could carry out two main scientific objectives:

1. The detection and characterization of Earth-like planets orbiting other stars
2. The imaging of astrophysical objects with unprecedented spatial resolution.

The most challenging of these objectives consists of the recording of IR spectra of terrestrial exoplanets that could detect signs of biological activity at distances up to 20 pc. In order to do this, the Darwin project is constructed around the new technique of "nulling interferometry", which exploits the wave nature of light to extinguish the light from a bright object (the central star in this case). At the same time the light from a nearby source (the planet) is enhanced. The contrast between planets and stars being the least in the IR wavelength region, that has been chosen for this mission. The result of the study was presented to the community in September of 2000 in Paris, France.

A more or less identical activity has been taking place in the United States within the context of NASA's Origins program. This program has very similar priorities in the context of understanding the origin of the Earth and the emergence and evolution of life on it, thus forming a solid base for collaboration on a number of programs.

2. Direct Detection of Terrestrial Exoplanets

All of the ground-based methods described previously during this conference will continue to refine our knowledge about planetary systems. But many techniques remain restricted towards the indirect detection of relatively massive planets. Space missions (e.g. COROT, Eddington, Kepler) designed for studying transits will eventually pick up lower mass (Earth-size) bodies, but relatively little information will be gathered in this fashion, since for statistical reasons, these missions will primarily observe very distant stars, thus not allowing detailed studies. The most important datum will be the frequency of Earth-like planets, which will allow for a proper design of direct detection experiments such as Darwin. The above mentioned missions are thus to be considered as true precursors to cornerstone level missions like Darwin. The main problem involved in the direct detection of an exoplanet of a size comparable to our own Earth - and located at a similar distance from its own star - is mainly one involving contrast and dynamical range. The central star (the Sun, the primary) outshines the planet in the visual wavelength range by a factor of at least 10^9. This problem is alleviated by going to the mid-IR where the planets thermal emission peaks (a terrestrial planet is in this case defined as one of roughly the same size as the Earth and of the same surface temperature - $\sim$ 270K - thus having its peak emission at 10 μm). Even at these wavelengths, the contrast is more than a factor of 10^6. The star and planet will be very near each other on the sky, and we need to devise a way of extinguishing the light from the star. Different coronographic methods (in space) have been evaluated, and albeit having the capability of achieving the scientific objective of detecting the exoplanet, these methods do not lend themselves to a large enough search space unless the telescope is extremely large. Lately it has been suggested to fly coronographic systems operating in the visual wavelength range in space. A 5-m to a 10-m diameter monolithic telescope could then suffice. A 10-m class coronograph operating in the visual could detect and study the Earth around 100 - 150 of the closest solar-type stars. Nevertheless, the stringent requirements on the optical surfaces may be insurmountable in the time frame considered for the Darwin project (launch in 2014). As a contrast, the Darwin model mission nulling interferometer described below, operating in the mid-IR, could detect and study the Earth in orbit around more than 500 stars in the solar neighborhood. Besides nulling interferometry, another method that has been suggested is the "densified pupil" technique. The nulling interferometry technique was selected for the Darwin study because of its relative simplicity and maturity at the time.

2.1. Nulling Interferometry

Nulling interferometry can most simply be described by considering two apertures, separated by a baseline D. One now points the two telescopes towards the same star, and connects the light output of the two units. If the optical path lengths of both apertures are the same, the amplitudes of the electromagnetic radiation will interfere. This is interferometry in the classical sense, producing a set of dark and bright bands - so called fringes. If we instead now make the light from one of the telescopes arrive at the site of beam combination with an added phase shift, π, the light along the optical axis will instead interfere destructively (since the dark fringe appears on top of the star). At the same time, waves arriving from a small angle, θ, away will interfere constructively. This separation will depend on the distance between the two telescopes. If we now assume that we have a star, which is orbited by a planet located at an angle θ away, we can extinguish the light from the primary and isolate the planetary light. The contrast between the star and planet is now determined by light leaks from the "central null" - due to imperfections in the optics and jitter of mechanical components. By using more telescopes it is possible to create a more complex transmission pattern. The actual pattern depends on the number of apertures, and the geometrical configuration. In the Darwin configuration we have 6 telescopes in a hexagonal pattern, and with all telescopes equidistant from a central beam combiner. Then the pattern is roughly doughnut shaped. It is now possible to "tune" the array to each individual star that is observed, such that the transmission ring is located on top of the so called habitable zone (see below). The signal also needs to be modulated, in order to separate out an eventual planetary signal from any background (such as exo-zodiacal light - dust in the target system radiating as a blackbody at $\sim$ 300K) or to discriminate between different combinations of planets in the observed system. This can be performed either by the rotation of the array of telescopes, switching between different combinations of apertures or by a combination of both. The last option is currently the baseline for Darwin.

3. Biomarkers

A major goal of the Darwin mission is to investigate if the conditions on any terrestrial exoplanet would allow life as we know it to exist and indeed if it already exists. In order to do so we need to define what life is, and how life as we understand it interacts with its environment in an observable way. Life contains information; life is self-replicating; life evolves; and life influences its environment. We are attempting to detect these attributes of life, through ("very") remote sensing, at interstellar distances. At first this goal appears hopeless. It has been found, however, in the last twenty years, that the simultaneous detection of water - H_2O - and molecular oxygen at a temperature of about 300K is a clear indication of life as we know it. This is because oxygen is one of the most reactive substances there is. If all life on the Earth was removed suddenly - bacteria, green plants, etc. - all of the free oxygen in the Earth's atmosphere would disappear in the geologically short time of 4 million years. The atmosphere of the Earth is out of equilibrium, as is evidenced by a comparison with models or with the situation in the other terrestrial planets in the solar system - Mars and Venus. This disequilibrium is caused by the living things on our planet. Previous to life being dominated by oxygen generating species, the atmosphere of the early Earth was out of equilibrium by methane, CH_4.

The criterion on temperature will define a habitable zone around each individual star. Strictly speaking, the surface temperature of a planet will depend not only on the energy input from the primary, but also on the atmospheric pressure and composition. Our own Earth, for instance, would be significantly colder without its greenhouse effect, caused by CO_2 and CH_4. Since *a priori* we have no idea about the presence and/or composition of any eventual atmospheres, we will have to use this criterion with some care in the individual case.

We mentioned above that we wish to observe in the mid-IR in order to make the detection problem more tractable because of a lessened contrast. Within the wavelength range of 5 μm to 20 μm we find important absorption features of water, carbon dioxide and ozone. Ozone has been shown to be a good tracer of oxygen since its absorption feature in the spectrum shows a logarithmic dependence on the abundance of molecular oxygen. The downside of using ozone as a tracer is that it is easily saturated. Very early in the history of life on our planet the O_3 saturated, and since then it has been possible to - remotely - determine the level of biological activity on Earth. The actual content of O_2 during the first half of the history of living things on our planet was significantly lower than it is today. With a spectral resolution, $\lambda/\delta\lambda$ = 20 - 40, we can detect all of the features mentioned above. We have to remember, however, that this refers to our Earth as it is today. The oxygen level in our atmosphere has been relatively high only for the last 20 % - 30 % of the Earth's history. Although, it is now more or less generally accepted that life arose on the Earth immediately after the era of bombardment, i.e. $3.8\times\ 10^9$ years ago, it remained in the sea, and at a relatively simple level until just about 600 million years ago. This was the time of the so-called Cambrian explosion, when most if not all of the phyla we can see today had their origins. Life until then was dominated by methane-producing species. If we define our "remote sensing" criterion such that life is indicated by a disturbing of the equilibrium of a terrestrial planet's atmosphere, we need to also take this evolutionary aspect into account.

4. The Darwin Model Mission

The current mission scenario is to be taken as a model that can fulfill the stated scientific objectives, but which may look quite different when aspects of international collaboration with NASA (see below) are taken into consideration. It consists of six 1.5-m telescopes, which transmit their input beams to a beam combiner satellite. The individual telescopes - each mounted on a separate spacecraft - are kept to within the required precision of their relative positions by utilizing a metrology system, which includes laser metrology, radio frequency goniometry, and the tracking of interferometric fringes from a bright guide star. In the case of the planet-finding part of the mission this latter requirement is not going to be a problem, since the search for exoplanets will be carried out around relatively nearby - and thus relatively bright - stars. The primary in each system can thus be used as a guide star for both pointing and fringe tracking for the adjustment of positions. Final adjustment of path lengths and the required phase delay is then introduced in the beam combiner satellite, where detection is also carried out. The system operates between wavelengths of 5 μm and 20 μm and requires passive cooling of all optical components to below 40K in order to reduce the thermal background. Because of this latter requirement on temperature, all power generating functions (computing, transmitting of data to Earth, laser metrology) is carried out from a non-cooled communications satellite. All 8 spacecraft are deployed and kept flying in formation in an orbit around the L2 sun-Earth Lagrangian point. Launch is foreseen with an Ariane 5, and the Darwin parameters are well within the envelope of that launcher. In the planet-finding mode, Darwin utilizes baselines between 40-m and 250-m. A separate beam combiner table on the central spacecraft is used for "normal" Michelson interferometry in an imaging mode. In imaging mode, baselines of up to 1 km are foreseen. In this mode, objects such as star-forming regions, active galactic nuclei (AGNs), the core of our own galaxy, black holes and very early galaxy formation, will be studied at unprecedented spatial resolution.

5. Technology Development and Implementation

An ambitious technology program has been initiated in order to develop the required items such as the nulling interferometry, metrology, and formation flying. Development of the required optical components such as polarizers, beam splitters and achromatic phase shifters are also being initiated. The following is a summary of the current elements in the Darwin technology program:

- Metrology:
    1. Radio Frequency (RF) ranging - RF position system used for deployment, coarse acquisition
    2. Laser metrology - high precision optical metrology (HPOM) for fine acquisition
    3. Fringe sensor - interferometric fringe tracking for the control loop of the Attitude and Orbital Control System
- Actuators:
    1. FEEP - Field Emission Electric Propulsion - mN and μmN thrusters with 1 mN $(\mathrm{Hz})^{-1/2}$ noise
    2. mN cold gas thrusters
- Control software:
    1. Deployment
    2. Optical Path Difference Control (using fringe sensor and/or HPOM)
    3. Formation flying command and control
- Optical Components:
    1. Achromatic phase shifter
    2. Optical delay line (SMART-2 verification)
    3. Wavefront filter (monomode fiber)
    4. Amplitude / Polarization matching units
    5. Integrated optics at 5 - 18 μm wavelength

Further programs have been initiated in the area of detectors, coolers, interferometric configurations, beam combination and data post-processing. Several precursor missions and projects are planned in order to implement Darwin in a timely and efficient manner. The SMART-2 mission is planned for 2007. Being primarily intended as a test flight for the LISA gravitational wave detector mission, it nevertheless lends itself efficiently for a formation flying qualification flight, since it needs a two component spacecraft for proper LISA technology verification. On this flight, software and hardware required for formation flying, as well as the metrology, is planned for test. Accordingly:

1. Formation flying
   (a) Deployment
   (b) Collision avoidance, Failure Detection, Isolation & Recovery (FDIR)
   (c) Radio Frequency Metrology
2. Precision formation flying
   (a) Along one axis (only two spacecraft)
   (b) Accuracy (about 1 μmm)
   (c) High precision optical - RF metrology
3. Optical delay line (ODL)
   (a) ODL used to find and track fringes
   (b) μm-propulsion used to find fringes
4. Trade-off between FEEP and micron cold-gas propulsion systems

Nulling interferometry itself will first be tested on the ground. Currently, the objective of two industrial breadboard designs, it is intended to carry out the Ground based European Nulling Interferometry Experiment (GENIE) in 2006, based on the laboratory work and in collaboration between ESA and the European Southern Observatory.

The rationale for GENIE is the following:

1. Gain technological experience
2. Precursor science:
   (a) Exo-zodiacal disks
   (b) Study target systems
3. Unique and valuable science:
   (a) AGNs, star formation discs, brown dwarfs, etc.
   (b) Spectroscopy of hot Jupiters?

A final consideration is to provide European scientists with a nulling IR interferometer.

Another test flight (SMART-3) could be flown in 2009. This mission will be the objective of an assessment study during 2003, but could consist of a free-flying two telescope interferometer with a separate beam combiner. The important element of SMART-3 is to carry out a representative test of the complete Darwin mission (e.g., wide-band nulling interferometry at representative wavelengths, avionics, hardware elements). The Darwin mission could itself then be following in 2014. Darwin, because of its ambitious scope and technology requirements, lends itself very well to international collaboration. As mentioned above, NASA has a similar mission as the goal of the Origins program, the Terrestrial Planet Finder (TPF). Scientific collaboration and discussions have already been initiated with NASA, with the ultimate goal of attempting a joint Darwin-TPF mission. During the next 3 years leading up to 2006, both TPF and Darwin will be carrying out scientific and technological studies and development work - separately, but with joint membership on the science teams. Both the European and the NASA teams will be tasked to arrive at a final architecture that could be implemented in a joint scenario.

6. Conclusion

The Darwin model mission represents today a design that could answer one of the longest lasting scientific questions - if we are alone in the universe. The feasibility study has demonstrated the maturity of the existing plan, as well as providing a development plan that could improve the efficiency of the mission. It is also the current conclusion that free-flying nulling interferometers represent the most efficient way to carry out the scientific plan as defined above.