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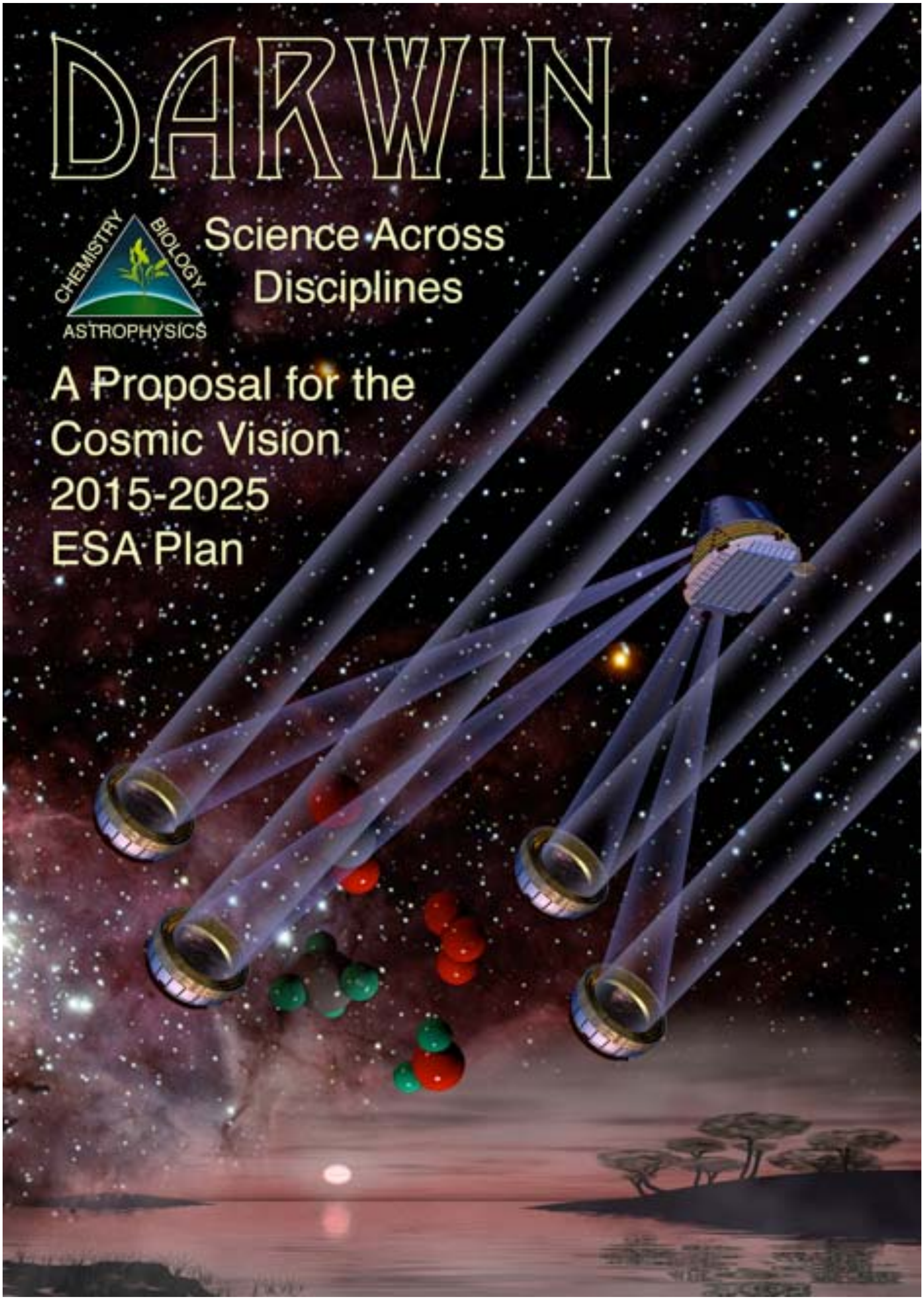


DARWIN

Science Across Disciplines

A Proposal for the Cosmic Vision 2015-2025 ESA Plan

DRAFT: 31 MAY 2007

This a **DRAFT** version
of the *Darwin* Proposal

Executive Summary

The recent discoveries of extra-solar planets are one of the great scientific and philosophical undertakings of our time. Aside from providing us with a wealth of information to understand the formation and structure of planets in a universal context, it captures the interest of both scientists and the public with the haunting prospect of the search for life in the Universe. ESA has clearly acknowledged this fact by making it one of its recommended themes of research in ESA's Cosmic Vision 2015-2025. We proposes a mission, called ***Darwin***, whose prime goal is the remote detection of life on extra-solar-planets. With this mission we want to understand what are the conditions for planet formation and the emergence of life? By its very nature, the *Darwin* mission fits extraordinarily well into one of the Grand Theme of the ESA's vision.

The mission goal is extraordinarily multidisciplinary It requires a wide range of disciplines including the planet formation, study of the planetary atmospheres, biology and life sciences to work together. A profound impact on a wide range of related disciplines may be expected from the *Darwin* mission outcomes.

Today about 200 planetary systems have been found outside our own Solar System including for some of them small planets with masses only few times the Earth's mass. The number of planetary systems with small planets is likely to growth with the setup of new generation instrumentations and the increase of performances. The recent announcement of the detection of a 5 Earth mass planet close to the Habitable Zone of its star is a good example of this intense ongoing activity on planet detection.

The *Darwin* mission is a facility to spatially resolve planetary systems made of rocky planet similar to the Earth and located in the habitable zone distance from its star, and to analyze the planet atmosphere in the 6 to 20 μm waveband. The spectroscopic analysis of the planetary emission shall allow to characterize the planet atmospheric condition and to look for traces of biological activities on the planet.

The baseline mission duration is 5 years. The observation sequences are built on about 200 targets observations with~ 50 planetary systems observed in spectroscopy, searching for atmospheric gases as CO_2, H_2O, CH_4 and O_3.

To reveal the faint emission of an Earth-like planet from the overwhelming flux of its host star, the planetary system needs to be very well spatially resolved from its star. In the mid-infrared, for nearby stars and planet located in habitable zone distance from their star, this requires a typical telescope diameter of 100 m. Considering this constraint, in space, a "nulling" interferometer concept has soon been identified as the best-suited technique to achieve mid-infrared spectroscopy of Earth-like planets around nearby stars. This facility has also the capability to make constructive imaging for general astrophysics high-resolution science.

A dozen of interferometer architectures have been proposed and studied at ESA and NASA during the past decade. These efforts on both sides of the Atlantic have resulted in a convergence and consensus on mission architecture made of a non-coplanar X-array, with four Collector Spacecraft and a single Beam Combiner Spacecraft.

A continue effort on the technology package needed for *Darwin* is ongoing both in Europe and in US. In these activities most of the required key technologies have been addressed and significant progresses made. The present team proposing the *Darwin* mission strongly support this ongoing effort and wish it could be vigorously continued at least at the level of these last 2 years. If one considers the progress made so far we believe that the key technologies for *Darwin* can be mature by 2010.

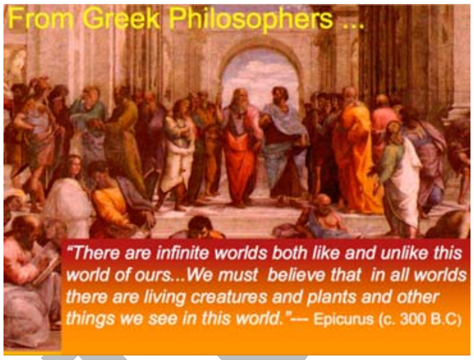
The proposed mission for the cosmic vision call is a timely an unprecedented opportunity for ESA to play a major role in an emerging field of research, at the intersection of astrophysics and life sciences, that captures a vivid interest in the research community.

1. Introduction

We propose an ambitious space mission to discover and characterize Earth-like planets and to search for evidence of life on them. The *Darwin* mission, undertaken within the Cosmic Vision programme with international collaboration, will address the most fundamental questions of humankind's origin and our place within the Universe.

1.1. Our Place in the Universe

Imaginative thoughts of worlds other than our own, perhaps inhabited by exotic creatures, have been an integral part of our history and culture. Giants of classic civilization, such as Democritos of Abdera (460-371 BC), Epicurus of Samos (341-270 BC) and the medieval philosopher and theologian Giordano Bruno (1548-1600 AD) imagined that we might not be alone in the Universe. These great thinkers were following an ancient philosophical and theological tradition, but their ideas, exciting as they might seem, were not based on observational or experimental evidence.



"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world."— Epicurus (c. 300 B.C)

The Greek philosophers,
by Raphael "School of Athens" (1509)

Our understanding of our place in the Universe changed dramatically in 1995, when Michel Mayor and Didier Queloz of the Geneva Observatory announced the discovery of an extrasolar planet. Geoff Marcy and Paul Butler in the United States soon confirmed their discovery, and the science of observational extrasolar planetology was born. The field has exploded in the last dozen years, resulting in nearly two hundred published planetary systems in 2007 (see http://exoplanet.eu/ and http://exoplanets.org/ for the most up-to-date list).

Most of these systems contain one or more gas giant planets very close to their parent star, and thus, do not resemble our Solar System. Although very interesting in their own right, they do not directly address the possibility of other worlds like our own. Observational techniques continue to mature, however, and planets with sizes and mass similar to the Earth may soon be within reach. Almost monthly, reports appear on our television screens of "Super-Earths," several times more massive than our planet and potentially cloaked in life- supporting atmospheres. The most recent examples, Gl 581c and GJ 436b, have ignited interest in extrasolar planet research across the globe.

Finding Earth analogues in terms of mass and size will be the focus of many ground and space-based research programmes in the coming decade. Finding evidence of habitability and life represents an even more exciting challenge. Semi-empirical estimates of the abundance of terrestrial planets, including their life-bearing frequency exist, many of them based on Frank Drake's famous equation. Unfortunately, these estimates are at best educated guesses, not because the equation *per se* is incorrect, but because nearly all of its factors are essentially undetermined, due to lack of observational tests.

Thus, the basic questions remain open: “Are there planets like our Earth out there?” and “Do any of them contain life?” However, unlike our forebears going back more than twenty centuries, we have the opportunity to address these questions with a real science experiment – the *Darwin* Mission.

If we want to understand our place in the Universe, we need to go to space and fly a mission like ***Darwin***.

The *Darwin* Mission will place a flotilla of five spacecraft at the second Lagrange point (L2) to observe nearby stars for evidence of terrestrial planets. These spacecraft will operate as a nulling interferometer, cancelling the intense glare of the star and revealing faint companions. Once targets are identified, *Darwin* will begin the process of spectroscopically characterizing the planetary atmospheres, searching for chemical signatures which may indicate the presence of life.

2. The *Darwin* Science Program

Searching for a phenomenon as subtle as life across parsecs of empty space may look hopeless at first glance, but considerable observational, laboratory, and theoretical effort over the past two decades is leading to the consensus that this is not the case. The *Darwin* science program is the logical climax of these efforts, and its goals could not be more ambitious and profound: discovering other worlds like our own and examining them for evidence of extraterrestrial life.

We begin by asking what is Life? A living being is a system that contains information and is able to replicate and evolve through random mutation and natural selection. Although this definition appears overly generic (for example, it includes computer viruses), consideration of possible storage media for Life’s information leads to a number of specific conclusions.

Macromolecules appear to be an excellent choice for information storage, replication, and evolution. Specifically, carbon chemistry is by far the richest and most flexible opon. The need for rapid reaction rates between macromolecules argues for a liquid solution medium, and based on chemical abundances in the universe, the most logical, although not necessary unique path for life to take is carbon chemistry in water solution (Owen, 1980). Such chemistry produces a number of gas phase biological indicators.

The logic of the *Darwin* science program follows directly: we must search for habitable planets – those where liquid water can exist – and investigate their atmospheres for biosignatures – the gas products of the carbon macromolecule chemistry we call Life.

2.1. Extrasolar Planetology in 2007

2.1.1. The Era of the Planet Hunters

The discovery of a planet orbiting the star 51 Pegasi (Mayor & Queloz 1995) marked the birth of a new field of astronomy: the study of extrasolar planetary systems. Since then, more than 200 planets outside our own Solar System have been discovered. These planets most closely resemble the gas giant planets, with masses in the range

20-1000 $M_\oplus$, but many of them are either in highly eccentric or very small (0.1-0.01 AU) orbits. Such planets have surface temperatures up to 1200K, and are hence known as “Hot Jupiters”.

Hot Jupiters are now explained quite naturally by inward migration, most likely due to tidal interactions with the circumstellar disk during their formation. We have also learned that Hot Jupiters preferentially form around higher metallicity stars: almost 15% of solar-type stars with metallicity greater than 1/3 that of the Sun possess at least one planet of Saturn mass or greater.

Despite considerable effort, no true solar system analogue has been found, and the lowest mass exoplanets range from 5-7 $M_\oplus$. The inward migration scenario appears incompatible with small rocky planets, and it is currently uncertain whether such worlds could coexist within currently known planetary systems.

Excluding known Hot Jupiter systems leaves us with 85% of high metallicity stars as potential hosts of terrestrial planets. A certain fraction of these will have gas giants in longer period orbits. The implications of such “true” Jupiters on the existence and habitability of Earth-like planets is an active field of planet formation theory.

2.1.2. Planet Formation Theory

Planets form within disks of dust and gas orbiting newly born stars. Even though not all aspects are yet understood, growth from micrometer dust grains to planetary embryos through collisions is believed to be the key mechanism leading to the formation of at least terrestrial planets and possibly the cores of gas giants.

As these cores grow, they eventually become massive enough to gravitationally bind nebular gas. While this gas accretion proceeds slowly in the early phases, it eventually runs away to allow the formation of a gas giant within the lifetime of the gaseous disk. Terrestrial planets, being closer to the star, empty their feeding zone before growing massive enough and must rely on distant gravitational perturbations to induce further collisions. Their growth thus occurs on longer timescales. Therefore, the early presence of long-period gas giants may be a prerequisite to the formation of terrestrial planets. The Hot Jupiters did not fit into this picture, however.

Caught by surprise at the time of their discovery, theory has since made considerable progress in understanding the known exoplanets. Extended core-accretion models can now be used to compute synthetic planet populations allowing a statistical comparison with observations (see figure XXX). While these models are not terrestrial planet formation models (they are initialized with a seed of 0.6 $M_\oplus$), they show that if planetary embryos can form, only a small fraction of them will grow fast enough and big enough to eventually become giant planets. Given that we detect gas giants orbiting about 7% of the stars surveyed, *Darwin*’s harvest of terrestrial planet should be very significant indeed.

2.1.3. Habitability

The circumstellar Habitable Zone (HZ) is defined as the region around a star within which an Earth-like planet can sustain liquid water on its surface, a condition necessary for photosynthesis. Within the HZ, starlight is sufficiently intense for a greenhouse atmosphere to maintain a surface temperature above 273 K, and low enough not to initiate runaway greenhouse conditions, which can vaporize the whole water reservoir and allow photodissociation of water vapor and loss of hydrogen to space (Kasting et al, 1993).

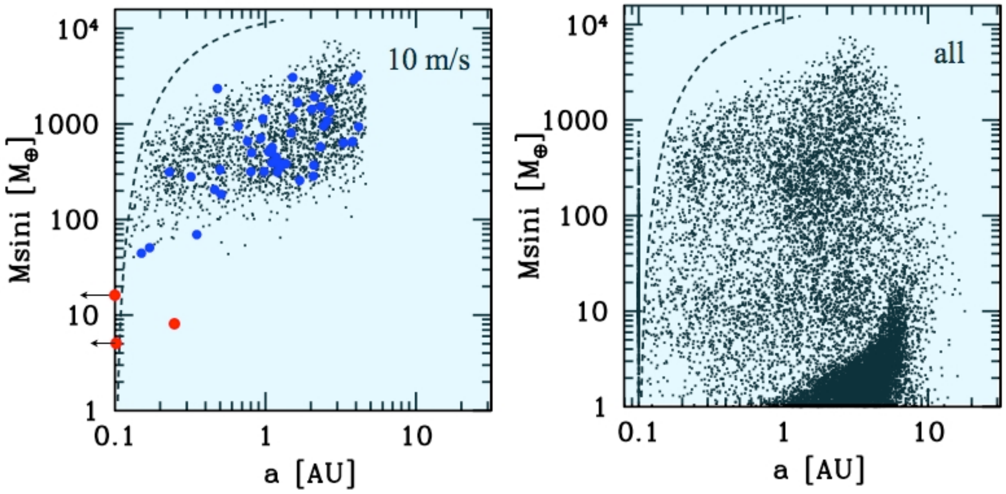


Figure XXX: Extrasolar planet population synthesis. Models based on the core accretion scenario can be used to predict the expected planet population orbiting solar-type stars. Left: The planets potentially detectable with radial velocity measurements with a precision of 10 m/s. The blue dots represent planets actually detected orbiting solar type stars, while the red dots are the three planets recently detected in orbit about the M dwarf Gl 581 (the two inside 0.1 AU have been put on the y-axis, since current models cannot compute planets inside this limit). Right: Underlying population of planets. We note that the majority of embryos do not grow to become gas giants, leaving many detectable lower-mass planets. While these models are currently applicable only to solar type stars, we expect the same trends to hold true for lower mass stars such as M types. In this respect, the recent discovery of a 5 $M_\oplus$ planet orbiting Gl 581 is very promising.

Planets inside the HZ are not necessarily habitable, They can be too small, like Mars, to maintain active geology and to limit the gravitational escape of their atmospheres. They can be too massive, like HD69830d, and have accreted a thick H_2-He envelope below which water cannot be liquid. A planet that is depleted or too rich in water, due to different accretion history, may not offer favourable conditions for the emergence of life. However, planet formation models predict abundant *Earth-like* planets with the right range of masses (0.5 - 8 $M_\oplus$) and water abundances (0.01-10% by mass) (Raymond et al. 2006a,b). Figure XXX shows the limits of the continuous HZ as a function of the stellar mass. The *continuous* HZ is the region that remains habitable for at least a billion years.

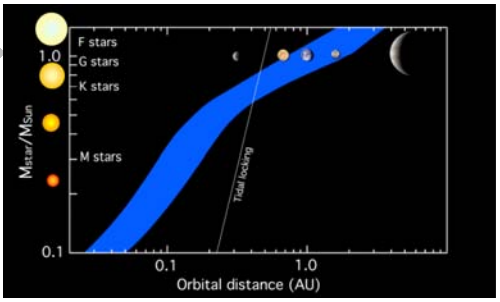


Figure XXX: Continuous habitable zone (blue region) around M, K, G, F stars. The region around the Sun that remains habitable during at least 5 Gyrs goes approximately from 0.76 to 1.63 AU.

Chemolithotropic life, thriving in the interior of the planet without using stellar light, can still exist outside the HZ. The associated metabolisms – at least the ones we know on Earth – do not produce oxygen, however, and these life forms rely on very limited sources of energy (compared to sunlight) and electron donors (compared to H_2O on Earth). They catalyze reactions that would occur at a slower rate in purely abiotic conditions and they are thus not expected to modify a whole planetary environment in a detectable way. For this reason, the edges of the HZ delimit the circumstellar region where we can search for signs of extrasolar life but not the region where life is possible.

2.2. Characterizing Exoplanet Atmospheres and the Search for Life

The range of characteristics of planets found in the Habitable Zone of their star is likely to exceed our experience with the planets and satellites in our own Solar System. In order to study the habitability of the planets detected by *Darwin*, and to ascertain the biological origin of the measured atmospheric composition, we need a comprehensive picture of the observed planet and its atmosphere.

In addition to providing the most favourable planet-star contrast and some potential biosignatures, the mid-IR wavelength (MIR) domain provides crucial chemical, physical, and climatic diagnostics, even at moderate spectral resolution. For example, the infrared light curve (i.e. the variation of the integrated thermal emission with orbital location) reveals whether the detected planet possesses a dense atmosphere suitable for life (Selsis 2003; Gaidos & Williams, 2004).

A low-resolution spectrum spanning the 6-20 µm region allows us to measure the effective temperature T_{eff} of the planet, and thus its albedo, as well as its radius R. Low-resolution MIR observations will also reveal the effects of greenhouse gases, including CO_2 and H_2O. Within the HZ, the partial pressure of CO_2 and H_2O at the surface of an Earth-like planet is a function of the distance from the star. Water vapour is a major constituent of the atmosphere for planets between 0.84 AU (inner edge of the HZ) and 0.95 AU. Carbon dioxide is a tracer for the inner region of the HZ and becomes an abundant gas further out. The exception to this is Venus-like planets, which have lost their water reservoir and accumulated a thick CO_2 atmosphere. Such planets can be identified as non-habitable by their high T_{eff}.

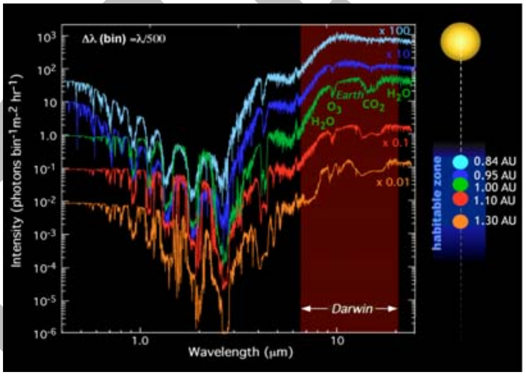


Figure XXX: Synthetic spectra of an Earth-like planet computed at different orbital distance across the solar habitable zone (Paillet et al., 2007)

Darwin will test the theory of habitability versus orbital distance by correlating the planets' spectral signature with orbital distance and comparing the results with grids of theoretical spectra, such as those shown in figure XXX.

2.2.1. Biosignatures

Darwin will have the ability to search for spectral signatures of life on planets found in the Habitable Zone of their star. Figure XXX shows that the mid-IR spectrum of Earth displays the 9.6-µm O_3 band, the 15-µm CO_2 band, the 6.3-µm H_2O band and the H_2O rotational band that extends longward of 12 µm. The Earth's spectrum is quite distinct from that of Mars and Venus, which display the CO_2 feature only.

The combined appearance of the O_3, H_2O, and CO_2 absorption bands is the most robust and well-studied signature of biological activity (Schindler and Kasting, 2000; Selsis et al. 2002; Des Marais et al., 2002). Despite variations in line shape and depth, atmospheric models demonstrate that these bands could be readily detected with a spectral resolution of 10–25 in Earth analogues covering a broad range of ages and and stellar hosts (Selsis, 2000; Segura et al. 2003; Kaltenegger et al. 2007).

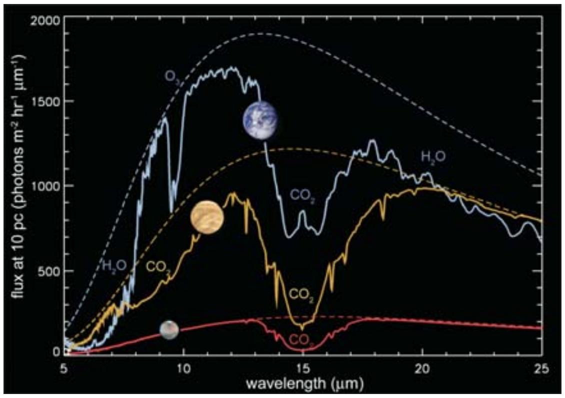


Figure 3. *Mid-IR spectra of Venus, the Earth and Mars as seen from 10 pc*

The ozone absorption band is observable for O_2 concentrations higher than 0.1% of the present terrestrial atmospheric level (Segura et al., 2003). The Earth's spectrum has displayed this feature for the past two and a half billion years.

Other spectral features of potential biological interest include methane (CH_4 at 7.4 µm), and species released as a consequence of biological fixation of nitrogen, such as ammonia (NH_3 at 6 and 9-11 µm), nitrous oxide (N_2O at 7.8, 8.5 and 17 µm) and nitrogen dioxide (NO_2 at 6.2 µm). The presence of these compounds would be difficult to explain in the absence of biological processes. Methane and ammonia commonly appear in cold hydrogen-rich atmospheres, but they are not expected as abiotic constituents of Earth-size planetary atmospheres at habitable orbital distances. Known abiotic routes do not produce nitrous oxide and nitrogen dioxide.

Methane, ammonia, nitrous oxide, and nitrogen dioxide do not produce measurable spectral signatures at low resolution for an exact Earth analogue. Nevertheless, they may reach observable concentrations in the atmosphere of exoplanets, due either to differences in the biosphere and the planetary environment, or because the planet is observed at a different evolutionary phase, as illustrated in figure XXX. Methane, for instance, was biologically maintained at observable concentrations during more than 2.7 billion years of Earth history from about 3.5 until 0.8 billion years ago (Pavlov et al., 2000). During the 1.5 Gyrs following the rise of oxygen (2.4 Gyrs ago), the spectrum of the Earth featured deep methane absorption simultaneously with ozone. The detection of a reduced species, such as CH_4 or NH_3, together with O_3, is another robust indicator of biological activity (Lovelock, 1980; Sagan et al., 1993).

The presence of H_2O, together with reduced species such as CH_4 or NH_3, would also be indicative of possible biological origin. Although a purely abiotic scenario could produce this mix of gases, such a planet would represent an important astrobiological target for future study.

The presence of nitrous oxide (N_2O) and, more generally, any composition that cannot be

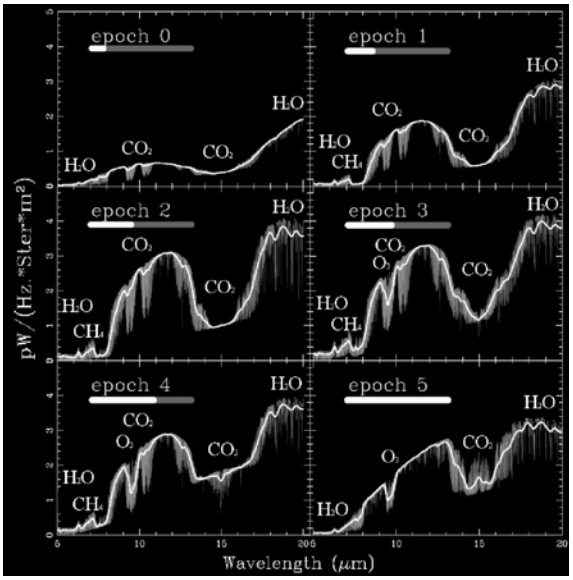


Figure XXX: Mid-IR synthetic spectra of the Earth at six different stages of its evolution: 3.9, 3.0, 2.6, 2.0, 0.8 Gyrs ago and the present (figure reproduced by a self-consistent abiotic atmosphere model would merit follow-up.

Finally, if biology is involved in the geochemical cycles controlling atmospheric composition, as on Earth, greenhouse gases will likely be affected and sustained at a level compatible with a habitable climate. Whatever the nature of these greenhouse gases, *Darwin* will be able to see their effect by analyzing the planet's thermal emission. This is a powerful way to give the instrument the ability to characterize unexpected worlds.

2.3. Comparative (Exo) Planetology

Over the decade since the discovery of 51 Peg, we have grown to understand that planetary systems can be much more diverse than originally predicted by theory. Our Solar System represents a very small sample of planets, after all. It is also clear that the current sample of extrasolar planets, although diverse, is incomplete: as observational techniques have improved, we have pushed the lower limit to the detected masses closer and closer to the terrestrial range. In the coming decade, this trend will continue, and our understanding of the diversity of lower mass planets will be critical to the understanding of the formation of terrestrial planets in general, and of the Earth in particular.

Growing the sample of terrestrial planets from the three in our solar system to a statistically significant sample will represent a quantum leap in knowledge. And, just as 51 Peg created the discipline of observational extrasolar planetology, this effort will engender a new type of science: comparative exoplanetology. It will allow for the first time a comparison of the orbital, physical and chemical characteristics of full planetary systems with our solar system and model predictions. Finally, this sample will also allow help answer one of the key questions related to *Darwin* science: How frequently are planets which are located in or near the HZ truly habitable?

2.3.1. Determination of planetary masses

`TBD`

2.3.2. Habitability and the Water Reservoir

The origin and evolution of liquid water on the Earth is an ideal example of the type of puzzle that comparative exoplanetology will address. Our planet (thankfully) orbits in the habitable zone of our star, but at least some of the water on Earth must have been brought in by primordial icy planetesimals.

Did the early Earth capture these planetesimals when they wandered into the inner solar system, or did our planet itself form further out and migrate inward? The answer is not clear at this point. What is clear is that habitability cannot just be reduced to a question of present-day location. The origin and fate of the water reservoir within the proto-planetary nebula is equally important.

By necessity, we have until now addressed this question using the very restricted sample of terrestrial planets in our own solar system: Venus, Earth and Mars. What have we learned? The in situ exploration of Mars and Venus taught us that all three planets probably evolved from relatively similar initial atmospheric conditions, most probably including a primordial liquid water reservoir. In all three cases, a thick CO_2

atmosphere and its associated greenhouse effect raised the surface temperature above the classical radiative equilibrium level associated with their distance to the sun. This atmospheric greenhouse effect was critical for habitability at a time when the young Sun was approximately 30% fainter than it is to-day.

At some point in the past, the evolutionary paths of Venus, Earth, and Mars began to diverge. For Venus, the combination of the greenhouse effect and a progressively hotter sun led to the vapourization of all liquid water into the atmosphere. After upward diffusion, the H_2O was dissociated by UV radiation, causing the loss of hydrogen to space by gravitational escape and erosion. Venus is today a hot, dry, and uninhabitable planet.

In contrast, Mars apparently experienced a 500 million year episode with a warm, wet climate, before atmospheric loss and a steady decrease in surface temperature trapped the remaining water reservoir in the polar ice caps and subsurface permafrost. Thus, Mars also became uninhabitable, but retained a fraction of its water reservoir.

Earth apparently followed an intermediate and complex evolutionary path, which maintained its habitability for much of the past five billion years. Early on, a thick CO_2 atmosphere compensated for the young Sun's reduced luminosity, and as the Sun brightened, atmospheric CO_2 was progressively segregated into carbonate rocks by the combined action of the water cycle, erosion, sedimentation of carbonate deposits on the ocean floors, and partial recycling via plate tectonics. This feedback cycle, which appears unique in the solar system, accounts for the preservation of Earth's oceans and habitability throughout most of its history.

If they exist, terrestrial planets with no analogue in the Solar System could be identified, e.g. the recently proposed Ocean-Planets (Léger et al., 2004; Selsis et al., 2007) that would form further than the snow line (~ 4 AU around a GV star) and migrate to the HZ, or closer. They would contain w 50% silicates and 50% water. Such objects would be the terrestrial analogues of hot jupiters and neptunes, and actually a new class of planets.

2.3.3. Comparative Planetology with Darwin

With *Darwin*, the sample of terrestrial planets will be extended to our galactic neighbourhood, allowing us to study the relationship between habitability and three families of parameters:

- Stellar characteristics, including spectral type, metallicity, and if possible, age; Our solar system illustrates the importance of understanding the *co-evolution* of each candidate habitable planet and its star.
- Planetary system characteristics, particularly the distribution, orbital characteristics, and chemical composition of terrestrial and gas giant planets.
- The atmospheric composition of planets in the habitable zone. Here again, the solar system sample points to the importance of ascertaining the relative abundance of the main volatile species: CO_2, CH_4, H_2O, O_2, O_3, NH_3…

The strategy for comparative exoplanetology with *Darwin* will be as follows: First, a comparison of stellar characteristics with the nature of the planetary system will capture the diversity of planetary systems. Then, *Darwin*'s spectroscopic data will reveal the range of atmospheric compositions in the habitable zone, a range that will be related to the initial chemical conditions in the proto-planetary nebula and, if stellar ages are available, to the effects of atmospheric evolution.

Correlating the general characteristics of the planetary system with the atmospheres of the individual planets will illuminate the interplay between gas giants and terrestrial bodies and the role of migration. For example, recent numerical simulations predict that the scattering effect of giant planets on the population of planetesimals plays a key role in the collisional growth of terrestrial planets, their chemical composition and the build-up of their initial water reservoir.

Thus, *Darwin* will allow us to address the question of habitability from the complementary perspectives of the location of earth-like planets with respect to their habitable zone, and of the origin, diversity and evolution of their water reservoirs.

2.4. Darwin General Astrophysics Option Programme

As an option, the *Darwin* mission includes a robust general astrophysics program in addition to its primary science goal of finding, characterizing, and searching for biosignatures on terrestrial exoplanets. In fact, the unique imaging and spectroscopic capability of *Darwin* will enable transformational science in a broad range of fundamental astrophysical topics. We highlight four research areas where this option of *Darwin* would make revolutionary advances: star and planet formation, the origin and growth of black holes, galaxy formation and evolution over cosmic time, and the nature and fate of the first generation of stars.

The keys to this scientific treasure chest are *Darwin*'s sensitivity, which is comparable to that of JWST, and most importantly, its angular resolution, which is a hundred times higher. These gains in resolution and sensitivity performance, compared to current ground-based instrumentation, are similar to those achieved at visible wavelengths over the last 4 centuries, as astronomy evolved from the naked-eye era before Galileo to the CCD era in the latter half of the 20th century

Star Formation Stars are the fundamental building blocks of the baryonic universe. They provide the stable environment needed for the formation of planetary systems and for the evolution of life. *Darwin* will impact our understanding of star formation in fundamental ways:

- *The Formation and IMF of Massive Stars* Young stars with masses >10M_{sun} are relatively rare in our Galaxy, with typical separations of 3-7kpc. They appear to be preferentially formed in ultra-dense proto-cluster environments. *Darwin* spectroscopic imaging and astrometry of young clusters throughout the Galaxy will provide unique diagnostics of highly ionized species in these systems, and will determine their internal dynamics and initial mass functions.
- *Stellar Multiplicity* Does the high multiplicity fraction of massive stars originate in the primordial fragmentation of the parent cloud core, or does it develop later in the evolution of the cluster by means of stellar dynamical processes such as three-body encounters?
- *Jet-Disk Connection* Forming stars launch powerful jets and bipolar outflows along the circumstellar disk rotation axis. *Darwin* will reveal the nature of the driving mechanism of jets by spatially resolving the jet-launching region. Are jets formed by ordinary stellar winds, the magnetic X-points where stellar magnetospheres interact with the circumstellar disk, or are they launched by magnetic fields entrained or dynamo-amplified in the disk itself?
- *Super-clusters and Starbursts* *Darwin* will resolve forming super-star clusters and starbursts in the Milky Way and nearby galaxies. Milli-arcsecond angular

resolution will allow us to peer inside clusters, to determine the volume density of stars, and thus to verify formation models in-situ.

Planet Formation Theory predicts that planets form in circumstellar disks over a period of 10^6 to 10^8 years. *Darwin* will provide a wealth of information about planetary systems at various stages of their evolution, revealing the origin of planetary systems such as our own, and thus helping to place our solar system into context. *Darwin* will be unique in being able to spatially resolve structures below 1 AU in nearby starforming regions, allowing us to witness directly the formation of terrestrial planets.

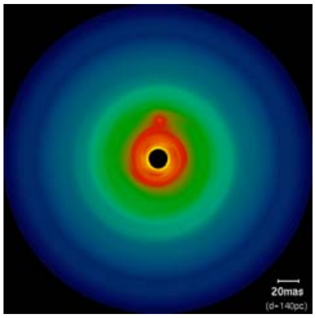


FIgure XXX: Hot accretion region of a protoplanet within a young circumstellar disk.– seen at 10mm as a bright spot in the disk (10 μm wavelength, Jupiter-mass Planet, T Tauri type central star, assumed distance: 140pc, field of view 20AU. from Wolf & Klahr).

Additional planet formation science includes:

- *Disk formation and evolution Darwin* will place constraints on the overall disk structure. For example, theory predicts that the vertical scale height is sensitive to grain size distribution within the disk. *Darwin* measurements will directly constrain grain growth, settling, and mixing processes in the planet-forming region.
- *Evidence of Forming Planets* Most models predict that proto-planets dramatically alter the structure of the disk and cause signatures that are much more evident than the planets themselves. These signatures range from gaps and spiral density waves in the case of young protoplanetary disks, to characteristic large-scale density patters in debris disks with mature planetary systems. *Darwin* will study the appearance and type of these signatures and their dependence on a number of factors, including the masses and orbits of the embedded planets and most importantly, the evolutionary stage of the circumstellar disk.
- *Disk Clearing within the Inner Few AU* The mid-infrared spectral energy distribution of protoplanetary and debris disks points to the existence of gaps. *Darwin* will determine if this clearing is due to the influence of already formed giant planets or if they are the result of viscous evolution, photo-evaporation, and dust grain growth.

Formation, Evolution, and Growth of Black Holes. How do black holes (BH) form in galaxies? Do they form first, and trigger the birth of galaxies around them, or do galaxies form first and stimulate the formation of black holes? How do black holes grow? Do they grow via mergers as galaxies collide? Or do they accumulate their mass by hydrodynamic accretion from surrounding gas and stars in a single galaxy? *Darwin* will probe the immediate environments of very different black holes, ranging from very massive BH in different types of active galactic nuclei (AGN), to the massive black hole at the centre of our own Milky Way, down to BH associated with stellar remnants.

Darwin will make exquisite maps of the distribution of silicate dust, ices, and polycyclic aromatic hydrocarbons (PAHs) in weaker AGN such as NGC 1068 out to redshifts of z=1-2. Brighter AGN can be mapped to a redshift of z=10, if they exist. For the first time, we will measure how the composition, heating and dynamics of the dust disks change with redshift. This will provide a clear picture of when and how these tori and their associated massive black holes grow during the epoch of galaxy formation.

The Galactic centre: The centre of our Galaxy contains the nearest massive black hole (3.6 x 10^6 M_o), a uniquely dense star cluster containing more that 10^7 stars pc^{-3}, and a remarkable group of high-mass stars with Wolf-Rayet-like properties. *Darwin* will be able to trace the distribution of lower mass stars and probe the distribution of dust and plasma in the immediate vicinity of the central black hole.

Galaxy Formation & Evolution Galaxy evolution is a complicated process, in which gravity, hydrodynamics, and radiative heating and cooling all play a fundamental role. Measurements of the detailed spatial structure of very distant galaxies at 1-2 micron rest frame wavelength, the location of the peak of the spectral energy distribution of nearby galaxies, will place essential constraints on galaxy formation models.

Unlike JWST, *Darwin* will resolve individual OB associations, massive star clusters, and their associated giant HII regions. By carefully selecting targets of a specific type, we can trace the evolution of galaxy structure as a function of redshift and environment. The evolution of metallicity with cosmic age and redshift can be mapped using various diagnotstics, including molecular tracers, ices, PAH bands, and noble gas lines that fall into the pass-band of *Darwin*. Figure XXX shows an example of the mapping power of *Darwin*.

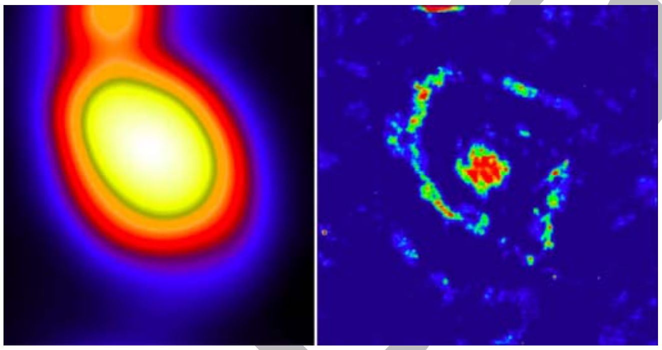


Figure XXX: Simulated images of an M51-type galaxy at z=3, as observed with JWST (left) and Darwin (right).

The First Generation of Stars The first stars formed in the early universe are thought to be quite different from the stars present today. The absence of metals reduced the opacity, allowing the first generation of stars to accumulate more gas and hence be considerably more massive (100 to 1000 Solar masses) and hotter than their modern counterparts. The first stars must have had a dramatic impact on their environment, creating giant HII regions whose red-shifted hydrogen and helium emission lines should be readily observable by *Darwin*

While JWST is expected to make the first detections of galaxies containing these “Population III” stars, *Darwin* will resolve scales of order 10 to 100 pc at all redshifts, providing the hundred-fold gain needed to resolve these primordial HII regions. *Darwin* will also test the current paradigm for the formation of the first stars. Are they truly isolated, single objects that have inhibited the formation of other stars in their vicinity, or are they surrounded by young clusters of stars?

Other Important Science The *Darwin* general astrophysics program includes a number of additional key science programmes:

- *Our home planetary system*: *Darwin* will easily measure the diameters, and properties of Kuiper Belt Objects, moons, asteroids, and cometary nuclei. Low-resolution spectro-photometry will constrain the natures of their surfaces, atmospheres, and environments.
- *AGB stars: Darwin* will provide detailed maps of the distribution of dust, and gas within the envelopes of oxygen-rich (M-type) and carbon-rich (C-type) AGB stars at distances out to the M81 group (4 Mpc) and in environments as extreme as the Galactic centre.
- *Stellar micro-lensing events*: Unhindered by dust obscuration, *Darwin* will map lensing events in the Galactic Center, thereby resolving the mass-distance ambiguity.
- *Eta-Carinae-like objects, LBVs, and Be stars. Darwin* will map the Roche Lobe overflow in the disks surrounding these objects anywhere in the Milky Way and Local Group.
- *Micro-quasars*: *Darwin* will probe the inner portions of relativistic jets via IR synchrotron emission and ions entrained in the jet sheath.
- *Supernovae: Darwin* will image the formation and evolution of dust, atoms and ions in supernova ejecta, and trace the structure of the circumstellar environment into which the blast is propagating.
- *Dark matter & dark energy: Darwin* studies of gravitational lensing by galaxy clusters, AGN, and ordinary galaxies will place unprecedented constraints on the structure of dark matter haloes at sub-kpc scales.

2.5. Synergies with other Disciplines

The primary *Darwin* science objective is inherently multi-disciplinary in character, uniting astronomy with biology, chemistry and physics. Often referred to as astrobiology, this interdisciplinary field also includes molecular biology, celestial mechanics and planetary science, including the physics and chemistry of planetary atmospheres and the characterization of exoplanetary surfaces. Finally, climatologists and ecologists will have the opportunity to study global influences on a statistical basis, increasing our understanding of climate regulation processes on Earth.

The general astrophysics part of the mission will create synergistic effects across multiple areas of research, including Solar System objects, nearby star (and planet) forming molecular clouds, the Galactic Centre, the interstellar medium in nearby galaxies, and high-redshift objects in the distant universe.

Finally, on the technological front, *Darwin* will drive development in such widely differing fields as material sciences, optical design, and spacecraft formation flying.

2.6. Darwin's Role in the Cosmic Vision Programme

Darwin fits extraordinarily well into the first Grand Theme of the Cosmic Vision 2015-2025 program: ***What are the conditions for planet formation and the emergence of life?*** Specifically, *Darwin* is explicitly designed to explore sub-topic ***1.2: From exo-planets to biomarkers,*** *i.e. Search for planets around stars other than the Sun, looking for biomarkers in their atmospheres, and image them.*

Darwin will also contribute significantly to theme ***1.1: From Gas and dust to stars and planets***, *i.e. Map the birth of stars and planets by peering into the highly obscured cocoons where they form.* Operating at mid-infrared wavelengths and with unprecedented spatial resolution, *Darwin* will be able to penetrate the dust obscuring the birthplaces of stars and planets and reveal the detailed physical processes driving star and planet formation.

In addition, *Darwin* science also addresses theme ***2: How does the Solar System work?*** Understanding the physics and dynamics of other planetary systems will certainly help to unravel the secrets of our own Solar System, including the issue of its long-term stability.

With its unprecedented high angular resolution capability, *Darwin* will advance Cosmic Vision theme ***3: What are the fundamental physical laws of the Universe?*** For example, determining the proper motion of stars in the gravitational field of the Galactic Centre with high accuracy will determine the properties of the black hole and of gravity itself.

3. The *Darwin* Mission Profile

3.1. Baseline Mission Scope

The *Darwin* mission consists of two phases, search and characterization, whose relative duration can be adjusted to optimize scientific return. During the search phase of the mission (nominally two years), *Darwin* will examine nearby stars for evidence of terrestrial planets. The number of stars that can be searched depends on the level of zodiacal light in the system and the collector diameters. As a baseline, we estimate this number under the assumption of a mean exozodiacal density 3 times that in the Solar System and collecting diameters of 2 m. Over 200 stars can be screened searching for planet around them in their HZ (Sect.4.3.3). The mission focuses on Solar Type stars, including the F, G, K and some M spectral types.

The number of expected planetary detections depends upon the mean number of terrestrial planets in the HZ, per star, η_{Earth}. Our present understanding of terrestrial planet formation (Sect.2.1.2) and the case of the Solar System where there are 2 such planets (Earth & Mars) and one close to it (Venus) point to a fairly high abundance of these planets. We assume thereafter $\eta_{Earth} = 1$.The COROT mission should give us a first idea on the abundance of small (hot) planets and *Kepler* should provide a precise value of this parameter, as well as the size distribution of these objets almost a decade before *Darwin* flies. An identified planet should be observed at least 3 times during the mission in order to characterize the orbit. A confidence level of 90% will qualify a detection (presence and orbit).

During the characterization phase of the mission (nominally three years), *Darwin* will acquire spectra of each detected planet with a resolution of 20, and sufficient signal-to-noise to be able to measure the equivalent widths of CO_2, H_2O, and O_3 with a precision of 20% if they are in abundances similar to those in the Earth's atmosphere.

Spectroscopy being more time consuming than detection, under the assumption of $\eta_{Earth} = 1$, it can be performed only on a fraction of detected planets. As shown in Sect.4.3.3, for planet sizes equal to that of the Earth, in 3 years *Darwin* can do the spectroscopy of CO_2 and O_3 on about 50 planets and that of H_2O on about half of them, although this last point requires further investigation. An optimization of the characterization part of the mission will be possible at the view of the characteristics, including the sizes, of the detected planets.

Extended Mission Scope

Whether the mission should be extended to 10 years and what strategy would be best suited will depends upon the results of the discoveries during the nominal first 5 years. Several directions can be foreseen: extending the observations to more M stars – only 10% of the observing time is presently dedicated to these stars ; searching for big, and easy to detect, planets around a large sample of stars ; additional observing of the most interesting already detected planets…

3.2. Darwin targets

`TBD`

4. Mission Design

4.1. The Darwin Concept and Its Evolution

In order to disentangle the faint emission of an Earth-like planet from the overwhelming flux of its host star, the planetary system needs to be spatially resolved. This, in turn, requires an instrument up to 100 m in diameter operating at mid-infrared wavelengths, since the angular size of the habitable zones around *Darwin* target stars ranges between 10 and 100 mas. A monolithic telescope of this size is obviously not feasible, particularly since the observatory must be space-borne and cooled to provide continuous coverage and sensitivity between 6 and 20 µm.

As a result, interferometry has been identified as the best-suited technique to achieve mid-infrared spectroscopy of Earth-like planets around nearby stars. In his pioneering paper, Bracewell (1978) suggested that applying a π phase shift between the light collected by two telescopes could be used to cancel out the on-axis star, while allowing the signal from an off-axis planet to pass through (figure XXX). This technique, referred to as *nulling interferometry*, has been at the heart of the *Darwin* concept since its origin (Léger et al. 1993).

In addition to the planetary flux, a number of spurious sources contribute to the signal at the destructive output of the Bracewell interferometer:

- Residual star light, referred to as *stellar leakage*, caused by the finite size of the stellar photosphere and by imperfect control of the interferometer
- The *local zodiacal background*, produced by the disk of warm dust particles that surround our Sun and radiate at infrared wavelengths
- The *exozodiacal light*, arising from the dust disk around the target star
- The *instrumental background* produced by thermal emission within the instrument.

Bracewell's original suggestion of rotating the array of telescopes can help disentangle the various contributions. The planet signal would then be temporally modulated by alternatively crossing high and low transmission regions, while the stellar signal and the background emission remain constant (except for the

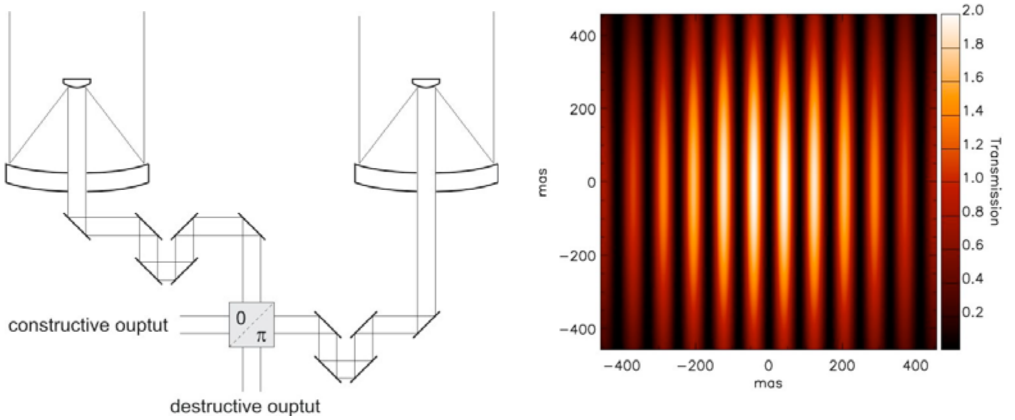


Figure XXX: Left: Principle of a two-telescope Bracewell nulling interferometer. Right: Associated transmission map, displayed at λ = 10 µm for a 25-m array. This fringe pattern is effectively projected on the sky, blocking some regions while transmitting others

exozodiacal emission). Unfortunately this level of modulation is not sufficient to achieve *Darwin's* goals, prompting a series of improvements to the strategy, including:

- Breaking the symmetry of the array to cancel all centro-symmetric sources, including the exozodiacal emission, by rotating the array;
- Performing faster modulation of the planet signal via time-variable phase shifts of the light beams.

Merging of these two ideas has lead to the concept of *phase chopping*, which is now regarded as a mandatory feature in space-based nulling interferometry. Figure XXX illustrates the principle of phase chopping. The outputs of two Bracewell interferometers are combined with opposite phase shifts (±π/2) to produce two "chopped states," which are mirrored with respect to the optical axis. Taking the difference of the photon rates obtained in the two chopped states gives the chopped response of the array, represented by the modulation map in figure XXX. This chopping process removes all centro-symmetric sources, including the stellar leakage and the exozodiacal emission.

Because the modulation efficiency varies across the field-of-view, the planet can only be localised and characterised through an additional level of modulation, provided by array rotation with a typical period of one day. The variation of the chopped planet photon rate with the rotation angle of the array appears in figure XXX `(XXX-where?)`. These data must be inverted to obtain the fluxes and locations of any planets that are present. The most common approach is correlation mapping, which is closely analogous to the Fourier transform used for standard image synthesis. The result is a correlation map, displayed for a single point source in figure XXX, which represents the point spread function (PSF) of the array. This process, illustrated here for a single wavelength, is repeated across the waveband, and the maps are co-added to obtain the net correlation map. The broad range of wavelengths planned for

Darwin greatly extends the spatial frequency coverage of the array, suppressing the side lobes of the PSF

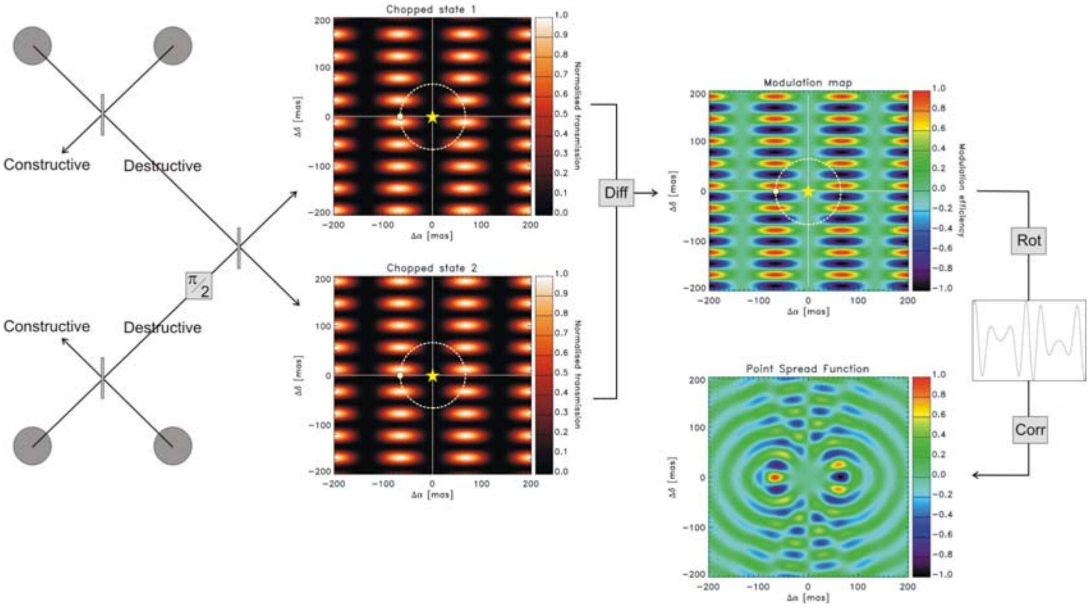


Figure XXX: Phase chopping for a four-element rectangular array of telescopes. Two conjugated chopped states are produced by combining the beams with different phases, and are used to extract the planetary signal from the background. Array rotation then allows the planet to be located, by means of a cross-correlation of the modulated chopped signal with a template

A dozen array configurations using phase chopping have been proposed and studied at ESA and NASA during the past decade. In 2004, the two agencies agreed on common figures of merit to evaluate their performance. The most important criteria are the modulation efficiency of the beam combination scheme, the structure of the PSF and its associated ability to handle multiple planets, the overall complexity of beam routing and combination, and finally, the number of stars that can be surveyed during the mission lifetime (see section XXX). Among the many configurations studied, the X-array has been identified as the most promising for the *Darwin* mission.

4.2. Mission Architecture

The desire for maximum mission efficiency, technical simplicity, and the ability to detect multiple planets around as many stars as possible has guided the selection of mission architecture. Additional top-level requirements include:

- Two observing modes: nulling for extrasolar planet detection and spectroscopy, and constructive imaging for general astrophysics;
- Placement at L2 for passive cooling and low ambient forces;
- Launch with a single Ariane 5 rocket or two Soyuz-ST/Fregat vehicles;
- The ability to search at least 225 candidate stars with an exozodiacal background of one zodi, or 150 stars with an exozodiacal background of 10 zodis;
- Detection and measurement of terrestrial atmosphere biosignatures as described in section XXX for at least 22 stars (with 1 zodi) or 15 stars (with 10 zodis);

- Time allocation of search as follows: G stars 50%, K stars 30%, F and M stars 10% each.

The effort to turn these requirements into a workable mission culminated in 2005-2006 with two parallel assessment studies of the *Darwin* mission. Two array architectures have been thoroughly investigated during these studies: the 4-telescope X-array and the 3-telescope TTN. These studies included the launch requirements, payload spacecraft, and the ground segment during which the actual mission science would be executed. Almost simultaneously, NASA/JPL initiated a similar study in the context of the Terrestrial Planet Finder Interferometer (TPF-I).

These efforts on both sides of the Atlantic have resulted in a convergence and consensus on mission architecture. The baseline for *Darwin* is a *non-coplanar* (or Emma[1]-type) X-array, with four Collector Spacecraft (CS) and a single Beam Combiner Spacecraft (BCS). This process also identified a back-up option, in case unforeseen technical obstacles appear: a *planar* X-array.

4.2.1. The Emma X-Array Architecture

Figure XXX shows the non-coplanar Emma X-array. Four simple Collector Spacecraft fly in a rectangular formation and feed light to the Beam Combiner Spacecraft located approximately 1200 m above the array. This arrangement allows baselines up to 168 m for nulling measurements and up to 500 m for the general astrophysics program.

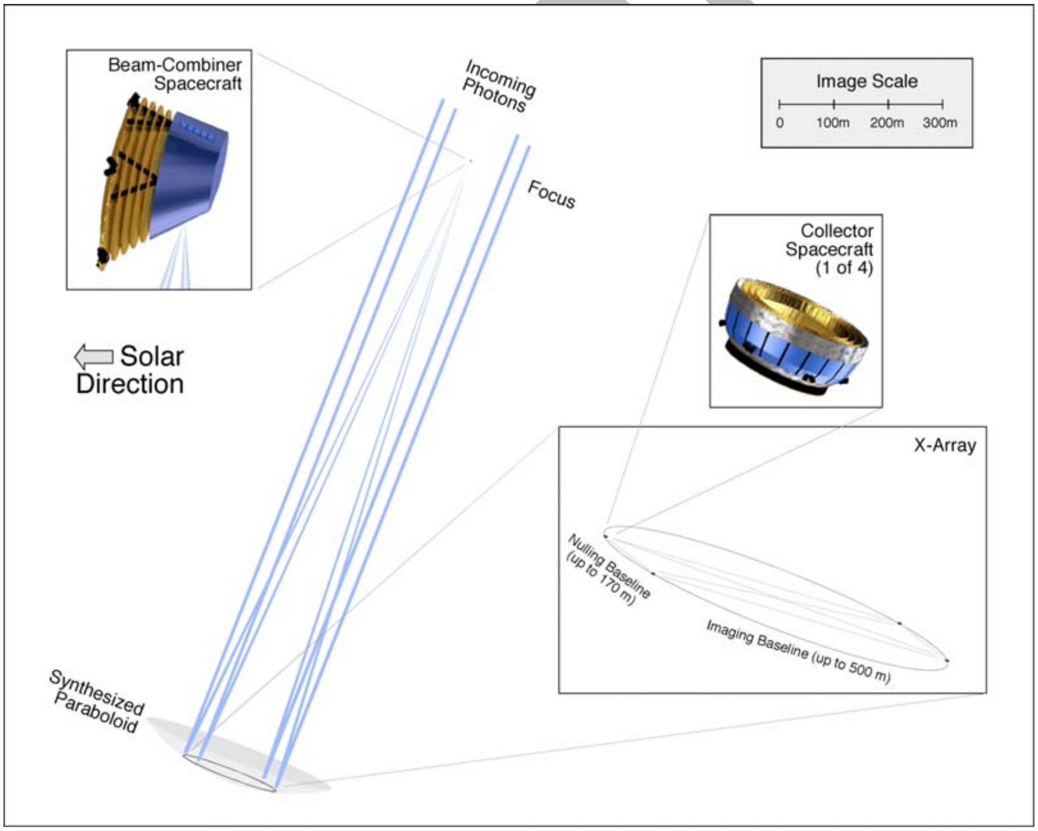


Figure XXX: The Emma X-array configuration consists of 4 Collector Spacecraft and a Beam Combiner Spacecraft. Spherical mirrors in the collectors form part of a large, synthetic paraboloid, feeding light to the beam combiner at its focus

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[1] Emma was the wife of Charles Darwin.

The X-array configuration separates the nulling and imaging functions, thus allowing independent, optimal tuning of the shorter dimension of the array for starlight suppression and the longer dimension for resolving the planet. Most other configurations are partially degenerate for these functions. The X-array also lends itself naturally to techniques for removing *instability noise*, a key limit to the sensitivity of *Darwin* (see section XXX). The assessment studies settled on an imaging to nulling baseline ratio of 3:1, based on scientific and instrument design constraints. A somewhat larger ratio of 5:1 may improve performance by simplifying noise reduction in the post-processing of science images (see section XXX).

Each of the Collector Spacecraft (CS) contains a spherical mirror and no additional science-path optics (additional components may be needed for configuration control). The four CS fly in formation to synthesize part of a larger paraboloid—the Emma configuration is a single, sparsely filled aperture. Flexing of the CS primary mirrors or deformable optics within the beam combiner spacecraft will conform the individual spheres to the larger paraboloid.

The Beam Combiner Spacecraft flies near the focal point of this synthesized paraboloid. Beam combination takes place on a series of rigid optical benches arranged within the BCS envelope. The necessary optical processing includes:

- Transfer optics and BCS/CS metrology;
- Correction and modulation, including optical delay lines, tip-tilt, deformable mirrors, wavefront sensors, and beam switching;
- Spectral separation to feed the science photons into 2-3 separate channels;
- Beam mixing and phase shifting;
- Recombination, spectroscopy, and detection.

The collector and beam combiner spacecraft use sunshades for passive cooling to 40 K. An additional mechanical refrigerator within the BCS cools the detector assembly to below 10 K.

Due to the configuration of the array and the need for solar avoidance, the instantaneous sky access is limited to an annulus with inner half-angles of 46° and 83° centred on the anti-sun vector. This vector transits the entire celestial sphere during one Earth year, hence giving access to almost the entire sky.

For launch, the collector and beam-combiner spacecraft are stacked within the fairing of an Ariane5 vehicle. Total launch mass is 6.6 tonnes, which is ample (Sect.7). Table XXX lists key parameters of the *Darwin* Emma X-array. These values represent the results of the various assessment and system level studies conducted by ESA and NASA.

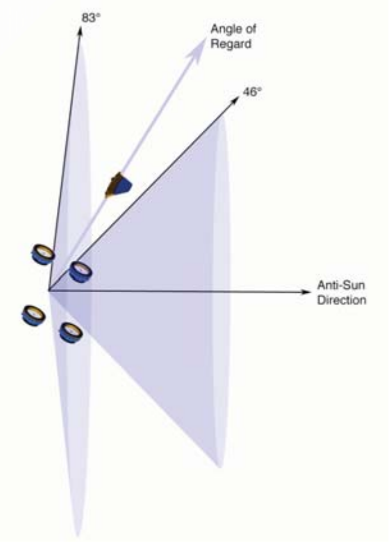

Figure XXX: The Emma X-Array can observe the entire sky between 46° and 83° from anti-Sun direction

Table XXX: Key *Darwin* parameters

Item	Value or Comment
Collector Spacecraft (CS)	4 free-flyers, passively cooled to <50K
CS Optics	Lightweight spherical mirrors, diameter *ca.* 2.0 m, no deployables
CS Array Configuration	X-array with aspect ratio 3:1 – 6:1 (to be optimized)
Available Baselines	7 m to 168 m Nulling, 20 m to 500 m Imaging option
Beam Combiner (BCS)	1 free flying spacecraft, passively cooled to <50K
Beam Combiner Optics	Transfer, modulation, beam-mixing, recombination, spectroscopy
Detection	Mid-IR detector ca. 500 x 8 nulling, (300 x 300 Imaging option) pixels, cooled to < 10 K
Detector Cooling	Low vibration refrigerator
Telemetry	Require ca. 1 GBit /s, direct downlink from BCS
Operating Wavelength	6-20 µm. Includes H_2O, O_3, CH_4, CO_2 signatures
Field of View	Typically 1 arcsec at 10 µm
Null Depth	10^5, stable over ~ 7 days
Angular Resolution	5 milliarcsec at 10 µm for a 500 m baseline, scales inversely
Spectral Resolution	25, possibly 300, for exo-planets; 300 for general astrophysics
Field of Regard	Annular region between 46° and 83° from anti-sun direction
Target Stars	F, G, K , M, at least 150 (10 exo-zodis) or 220 (3 exo-zodi)
Mission Duration	5 years baseline, extendable to 10 years
Mission Profile	Nominal 2 years detection, 3 years spectroscopy, flexible
Orbit	L2 halo orbit
Formation Flying	Radio Frequency and laser controlled
Station Keeping	Field Effect Electric Propulsion (FEEP) or cold gas
Launch Vehicle	Single Ariane 5 ECA or 2 Soyuz-ST / Fregat

4.3. Mission Performance

4.3.1. Detecting Earths

Darwin's instruments will encounter a number of extraneous sources (see figure XXX). The planetary flux must be extracted and analysed in the presence of these other components. The discrimination is performed by nulling the stellar light as much as possible, and by appropriate modulations (section XXX) that produce a zero mean value for the different background sources, for example, local zodiacal light, exo-zodiacal light, and thermal emission from the optics. Unfortunately, modulation cannot eliminate the *quantum noise* (sometimes referred to as photon noise) associated with these sources.

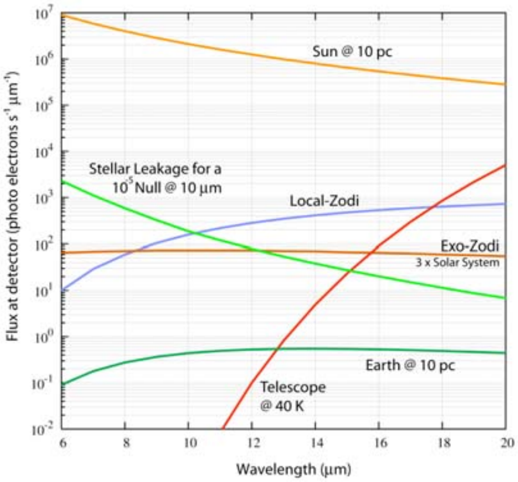

Figure XXX: Different flux sources for an Earth analog at 10 pc.

For a given integration time τ, the signal is proportional to the number of planetary photons (pl_flux.τ), and the quantum noise to the square root of the number of additional photons (fluxes.τ)$^{1/2}$. As described in the next section, additional noise arises from imperfections in the system such as stellar leakage. In order not to dominate the quantum noise, these imperfections must be very stable, with a flat Power Spectral Density (i.e. white noise), allowing the signal to noise ratio on the planet to increase as $\tau^{1/2}$.

4.3.2. Instability Noise

To estimate mission performance in a realistic way, we must take into account the possible imperfections of the instrument. In the case of *Darwin*, the main instrumental effects result from vibrations and thermal drifts of the spacecraft, which produce small fluctuations in the phase and amplitude of the input light beams and thereby instabilities in the interferometric null — a process similar to speckle noise in a coronagraph. The associated time-variable leakage of stellar photons, called *instability noise*, can mimic a planetary signal, and is generally not removed by phase chopping.

Reducing the contribution of instability noise to a harmless level, that is, below other noise sources, places strict requirements on configuration control: path length and amplitude variations should be less than 1.5 nm and 0.1%, respectively. This is only marginally compliant with state-of-the-art active control. Therefore, two techniques have been proposed and investigated to mitigate the influence of instability noise on mission performance.

The first solution, known as *spectral fitting*, arises naturally from the configuration of the X-array, in which the nulling baselines are de-coupled from the spatial resolution baselines. Stretching the array along the imaging baselines while keeping the nulling baselines unchanged shrinks the fringe pattern considerably. Because the overall transmission pattern scales as the wavelength, the transmitted planet signal becomes a rapidly oscillating function of wavelength, an effect which can be used to disentangle it from the slowly varying instability noise pattern. Having the ability to adjust the shape of the X-array would allow implementation of this technique in an optimal way.

The second solution, known as *post-nulling calibration*, also relies heavily on the geometry of the X-array. The constructive outputs of the pair-wise nulling beam combiners, which contain mostly stellar light, can be used as reference beams to calibrate the final output of the interferometer. Only the stellar component of the output signal produces fringes when combined with these reference beams, and hence the stellar glare can be isolated.

These two mitigation techniques represent a decisive advantage of the X-array concept compared to other architectures.

4.3.3. Search Strategy and Performance

Darwin mission performance is best expressed in terms of the number of stars that can be screened for the presence of habitable planets, and the number of follow-up spectroscopic observations that are possible.

The nominal mission is 5 yrs, 2 yrs for detection and 3 yrs for spectroscopy (Sect.3.1), of which about 70% is spent collecting data, the other 30% is spent moving the spacecrafts to change the interferometer geometry. In order to secure an accurate identification in the search phase, we require that the probability for detecting an Earth-like planet within the habitable zone at a signal-to-noise ratio (SNR) of 5 be 90% or greater.

ESA has conducted performance simulations for each star in the target catalogue, using the *DarwinSim* software to assess the required integration time to reach the required signal to noise ratio (SNR) for detection and spectroscopy. These requirements are a SNR of 5 for imaging and 10 for H_2O, CO_2 and O_3 spectroscopy (SNR of 10 on the underlying blackbody continuum emission, using a spectral resolution $\lambda/\Delta\lambda \geq 25$[1]). The *Darwin* target catalogue contains 625 carefully selected nearby main sequence stars (43 F, 100 G, 241 K and 241 M stars). The mission profile calls for 50% of the observing time to be spent on G dwarfs, 30% on K dwarfs, and 10% each on F and M dwarfs.

The level of exozodiacal emission is a key input parameter to these simulations. Although an active area of current research, the amount of exozodiacal emission around typical main sequence stars is largely unknown. Under the (debatable) assumption that it is symmetric around the target star, the exozodiacal emission will be suppressed by the chopping process, and will therefore contribute only to the shot noise. The simulations presented below assume an exozodiacal density of 3 zodis.[2]

Using an Emma X-array (6:1 configuration) with 2-m diameter telescopes and assuming an optical throughput of 10% for the interferometer, we estimate that about 200 stars distributed among the four selected spectral types can be screened during the nominal 2-year survey (Tab. XXX). *Darwin* will thus provide statistically meaningful results on nearby planetary systems. Figure XXX shows that nearby K and M dwarfs are the best targets in terms of Earth-like planet detection.

Assuming that each nearby cool dwarf is surrounded by one rocky planet of one Earth radius within its habitable zone, we estimate that only a fraction of the potentially detected planets can be fully characterised (i.e., examined for the presence of H_2O, CO_2 and O_3) during the subsequent 3-year spectroscopic phase (Tab. XXX). This number would be doubled or quadrupled for planets with radii 1.5 and 2 times that of the Earth, respectively. A comparable simulation effort at NASA using star count models confirms these predictions.

	1m	2m	3m
Screened	76	218	405
# F	5	14	30
# G	15	53	100
# K	20	74	152
# M	36	77	123
CO_2, O_3	17	49	87
# F	1	2	3
# G	4	8	15
# K	3	12	25
# M	9	27	44
H_2O	14	24	43
# F	0	1	1
# G	2	4	7
# K	1	5	10
# M	11	14	25

Table XXX: Expected performance in terms of number of stars screened and lanets characterised by spectroscopy fo arious telescope diameters. All stars are assumed to host an Earth-like planet. Estimates for H_2O spectroscopy are not final.

The diameter of the telescopes has a large

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[1] The required SNR of 10 for water vapour detection has still to be consolidated. For CO_2 and O_3, an SNR of 5 would actually be sufficient for a secure detection.

[2] In practice, exozodiacal densities below 10 times our local zodiacal cloud barely affect the overall shot noise level, while higher densities would significantly increase the required integration times.

influence on the overall mission performance. With 1-m telescopes, the number of targets screened would be reduced to about 100, while with 3-m mirrors, almost the whole star catalogue could be surveyed.

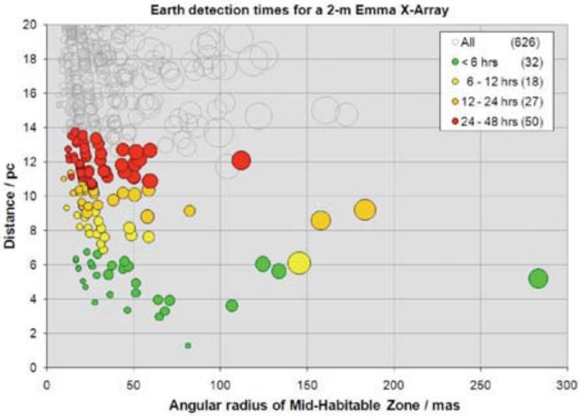


Figure XXX: Integration time needed for a 5σ detection of Earth-sized planets around each of the Darwin candidate targets, represented as circles proportional to their intrinsic diameter. Integration times longer than 24 hours are not shown, but are not precluded from the mission.

4.3.4. Image Reconstruction

These mission performance estimates are based solely on signal-to-noise ratio, disregarding the details of signal extraction and image reconstruction algorithms. In practice, data processing will be very important. For example, accurate orbit determination requires that the emission can be localised and tracked over time, while spectroscopy is only meaningful if the photons can be attributed to the right object. It is therefore very important that *Darwin* can resolve the emission from the multiple sources that might be present in a stellar system, including planets, lumps in the exozodiacal dust emission, background objects, etc. Image fidelity depends on a high quality PSF, such as that shown for the X-Array in figure XXX. As mentioned before, this configuration has the enormous advantage of allowing a separation of the nulling and imaging baselines.

Software development has been initiated on both sides of the Atlantic to address the image reconstruction needs of *Darwin*. Figure XXX shows the results of a reconstruction simulation using the Point Process Algorithm (PPA) in the case of a planetary system containing five Earth-like planets at radial distances 0.4 – 5.25 AU from a Sun-like star located at 15 pc. The 3:1 X-array configuration has been used to simulate the data set for a total integration time of 1 day. The simulation includes fundamental noise sources. Figure XXX demonstrates the capability of advanced data analysis tools to retrieve the actual arrangement of a planetary system, even with a non-optimal imaging configuration – a more elongated 6:1 X-array would produce even better results.

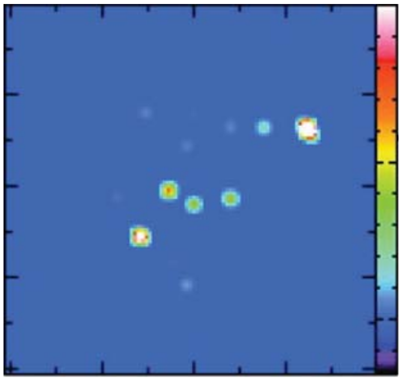


Figure XXX: PPA reconstruction of a five-planet system observed with a 3:1 X-array (Marsh et al., 2006).

4.4. Imaging for the General Astrophysics Program

A number of performance requirements determine the ultimate quality and hence the scientific productivity of the *Darwin* mission for the general astrophysical case. Table XXX summarizes these requirements, a number of which are described individually in the following paragraphs.

	Requirement	Goal
Maximum baseline [m]	500	2000
Minimum baseline [m]	20	10
Field of view [resolution elements]	100^2	1000^2
Dynamic range	1:100	1 : 1000
Spectral range [μm]	6 - 20	4 - 30
Spectral resolution	300	3000

Sensitivity: The 5σ point source sensitivities for *Darwin* in 20% wide bands centred at 8, 10, 13 and 17 μm is for an hour of observing are approximately 0.1, 0.25, 0.5 and 0.8 μJy. These sensitivities are comparable to those of the JWST mission.

Angular resolution The maximum foreseen baselines are 500 metres, corresponding to a spatial resolution of 5 mas at 10 μm.

Spectral range and resolution: The general astrophysics program exploits the same spectral range as needed for the characterization of exo-Earth atmospheres (6-20 μm). Extending this range to 4-30 μm would be desirable. At shorter wavelengths, stellar emission is relatively strong, opening up the possibility of interesting kinematic studies of the cores of galaxies, including our own. At longer wavelengths, important diagnostic spectral lines provide physical insights for key science goals. A spectral resolution of 300 allows for a proper determination of the continuum and broadband dust features and detection of important emission lines.

Image complexity The field of view is 0.5 arcsec at 10 μm for the planned pupil combination scheme. Typical *Darwin* maps will contain up to 100×100 independent pixels. This means that for complex objects at least 100^2 visibility measurements will be needed. This requirement is easily met by executing a full rotation of the array every 10 hours, a rate compatible with the primary exoplanet science. Figure XXX shows the excellent UV coverage that is possible during a single, 10 hour observation. These UV tracks produced the simulated *Darwin* image in Figure XXX — which image?

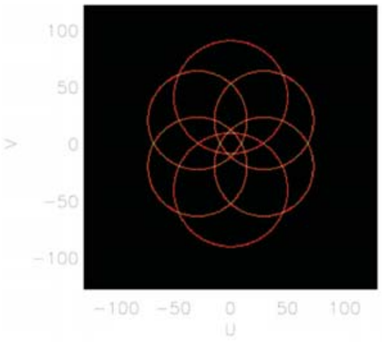


Figure XXX: UV coverage for a 10 hour Darwin observation.

Co-phasing: Two operating regimes exist for co-phasing the *Darwin* array. First, when a relatively bright point source (unresolved by the interferometer), the light of the target can be used to co-phase the array. The main difference between this mode and the nulling configuration is that the achromatic phase shifters are not needed. With a stability time scale of 10 seconds for the array (Alcatel study 2000), the sensitivity limit for self-fringe-tracking is about 10 mJy at 10 μm in a 0.5 arcsec aperture. This performance gives access to virtually all of the sources in the Spitzer SWIRE survey.

For targets with no such a point source, the preferred option for co-phasing is to use to the light from a nearby off-axis bright reference star. An efficient way of doing this is to combine the K-band light of a nearby bright star and the 6-18 μm light of the target to a common optical axis at the individual telescopes, and thereafter, to feed these combined beams into the central beam combiner.

Figure XXX shows a prototype for a possible beam combiner capable of carrying out both the nulling and imaging part of the *Darwin* mission.

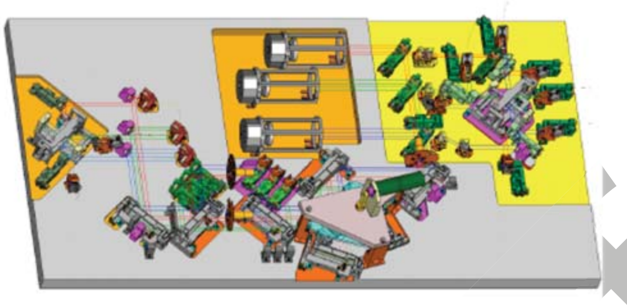


Figure XXX: Combined nulling / imaging beam combiner testbed. Image. (courtesy TNO/TPD, SRON, and Cosine)

5. Science Operations and Archiving

5.1. Data Science Operations Architecture and share of responsibilities

The Science Operations Center (SOC) will be responsible for science mission planning, data processing, and data product distribution to the *Darwin* science team and the wider scientific community. Because the data acquisition and calibration requirements are very different for the planetary (nulling) and general astrophysics (imaging) missions, options for the SOC beyond ESOC need to be considered. Computer networking and remote presence through videoconferencing will play a central role, allowing responsibilities to be spread among a variety of network-nodes at several institutes throughout Europe.

5.2. Archive approach

The site for active and legacy archives is TBD. The archive should include transmission `(XXX-what does this mean?)`, visibilities, and reduced image data, including the accompanying calibration files. A quick-look facility will allow rapid assessment and review of the data. Compared to other contemporary missions, *Darwin*'s data volume will be relatively modest and should present no storage challenges.

5.3. Propriety Data Policy

Although the detailed rules of data access are still to be determined, we anticipate that there may be different policies for the primary science and general astrophysics programs. Specifically, the baseline mission (nulling interferometry) will be conducted by ESA in cooperation with a dedicated team of *Darwin* scientists. Data rights would then follow guidelines adopted by ESA for missions similar in character (e.g., GAIA). In general, the science team is obliged to reduce the data and make the results public within a stipulated time. A peer-review process will almost certainly determine the general astrophysics targets. Following a call for Open Time observations, ESA will accept proposals from a Lead Scientist, who will act as the contact point between the Agency and the proposing community. In this case, the commonly adopted proprietary period is one year from the time of data release.

6. Technology and Mission Roadmap for *Darwin*

6.1. Darwin's Technology Roadmap

6.1.1. Essential Technology Developments for Darwin

The pre-assessment study of *Darwin* by Alcatel in 2000, and the assessment study by TAS and Astrium in 2006 determined that there is no technology showstopper for this ambitious mission. On the other hand, a number of key areas require focused attention and resources:

- *Formation Flying* of several spacecraft (SC) with relative position control of a few cm
- The feasibility of *nulling interferometry* in the 6 - 20µm range. Alcatel assumed a mean null depth of $<nl> = 10^{-5}$, relying on long integration times to beat down the contrast between the planet and star, ($3\ 10^{-8}$ at 7 µm and 10^{-6} at 18 µm for an Earth-Sun analogue). Based on evaluations of instability noise (XXX Sect.4.3.1-2), the common conclusion is that the null depth must be $<nl> = 10^{-5}$, and most importantly, stable $\sigma_{nl}(\sim 100h) < 3\ 10^{-9}$ at 7 µm;

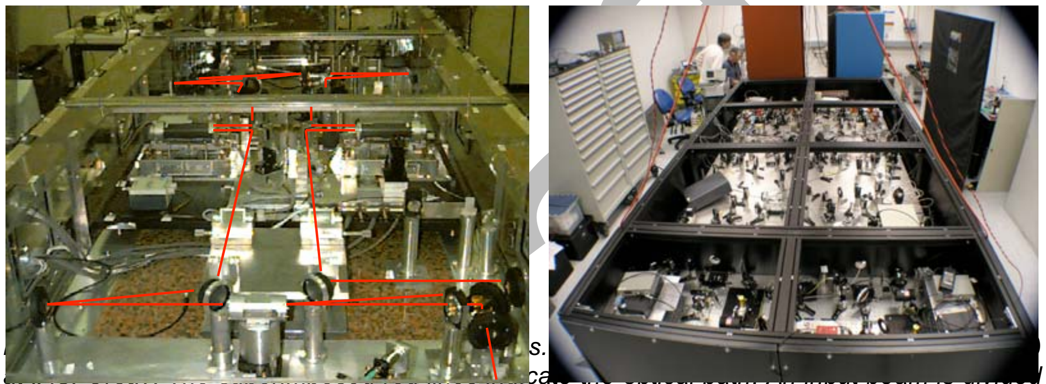
6.1.2. Currrent Status of Technology Development

Europe has devoted considerable resources, both intellectual and financial, to these technological issues since the initial Alcatel study. For example, ESA has invested approximately 20 M€ since 2000, with a significant ramp-up in the last 2 years. Several tens of Technology Research Programs (TRP) have been issued. NASA has run a parallel and very significant program in the USA. Most of the key technologies have been addressed and significant progress achieved.

For example, in the area of Formation Flying (FF), the TRPs "Interferometer Constellation Control" (ICC1 and ICC2) have developed nonlinear, high fidelity navigation simulators. Interferometer Constellation Deployment (ICD) at L2 has also been worked out. In the USA, analogous simulations and a 2D robotic breadboard (Figure XXX) have demonstrated the feasibility of formation flying. Finally, the PRISMA mission will test FF in space next year (Sect. XXX-6.2).

Figure XXX: The 2 robots of the Formation Control Testbed at JPL. Each robot carries cannisters of compressed air to float off a polished metal floor, and a mobile platform (shown tilted). The robots have completed their functional testing and should achieve their operational testing in 2007.

The investment in nulling interferometry research over the past seven years has also begun to pay off. The flight requirement is a null depth of 10^{-5} in the 6 – 20 µm domain. In Europe and at JPL (Fig.XXX), monochromatic experiments using IR lasers at 3.4 µm and 10.6 µm, have yielded nulls equal to or significantly better than 10^{-5}, Broadband experiments are also providing good performances, for example $2x10^{-5}$ for 18% bandwidth at 10 µm (Peters, 2007). Clearly, the technology of nulling interferometry is nearing maturity but it does not yet operate over the full *Darwin* bandwidth with the required mean value and, most importantly, the required stability. However, these encouraging results give us confidence that the *Darwin* goals will be met with continued effort and investment.



[illegible] s. [illegible] indicate the optical path. An input beam is divided into 2 parts to simulate the light coming from 2 different spacecrafts. The beams recombine in destructive or nulling interference mode. Right, The Planet Detection Testbed at JPL, which simulates a bright star and a faint planet. The planetary signal can be extracted from the global flux when the contrast ratio is below 2 millions.

Additional key technological developments in recent years include:

- Selection of the best *interferometer configuration*. Significant effort in this area since 2000 has identified the non-planar Emma X-Array as the optimal choice.
- *Achromatic Phase Shifters (APS)* which allow broadband destructive interference between the beams coming from different collectors. A comparative study currently running in Europe should identify the preferred APS technology.
- Space-qualified Delay Lines to balance the different optical paths to nanometre accuracy. A breadboard at TNO-TPD has demonstrated performance at 40K and may be included as a test payload in the PROBA 3 space mission (Sect. XXX-6.4).
- *Single Mode Fibres*, or Integrated Optics modal filters, that can operate in the full *Darwin* wavelength range, possibly split into 2 sub-ranges. Both chalcogenide and silver halide fibres have been demonstrated. Present performance results are preliminary.
- *Detector Arrays* with appropriate read noise and dark current. The Si:As Impurity Band Conductor (IBC) arrays developed for JWST appear to be fully compliant with *Darwin* requirements. A reduced-size version of the JWST 1024 x 1024

detector, e.g. 512 x 8 (300 x 300 in Imaging option), could be read out at the required rate with a dissipation of a few tens (hundreds) of µW. These devices exhibit high quantum efficiency (80%), low read noise (19 e^-), and minimal dark current (0.03 e^-/s at 6.7 K). Such performance permits sensitive observations, even at moderately high spectral resolution.

- Low vibration *Cryo-coolers* for the detector system. A European TRP has led to a prototype providing 5 mW of cooling power at 4.5 K. JPL scientists have demonstrated a system with 30 mW of cooling at 6 K.

6.1.3. Future Plans

The message from the last decade of *Darwin* technological development is clear:

If the Research and Technology effort that has been pursued in both Europe and the United States continues vigorously, Darwin's technology will be mature by 2010, allowing it to be selected as ESA's first L mission for launch in 2018-2020.

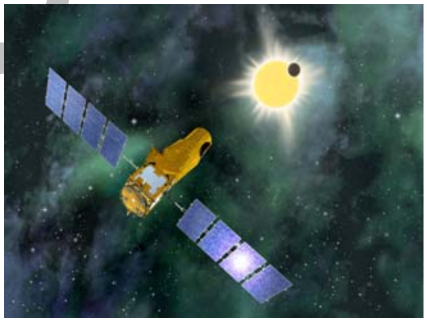
In addition to the European and American teams, the Japanese space agency (JAXA) has expressed interest in the mission and participating in the technology effort. Japan has considerable expertise in several key fields, including cryogenics with the AKARI mission and the preparation of ASTRO-F.

6.2. Precursor Missions

6.2.1. Exoplanet Discovery and Statistics

Corot (in operation)

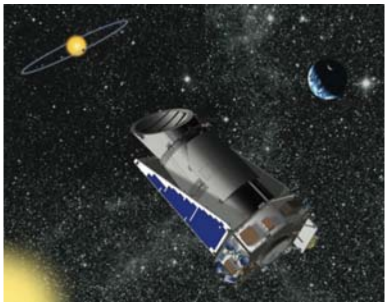
COROT is a CNES led mission that searches for planetary transits in front of stars. It was launched at the end of 2006 and commissioning is running smoothly. It has a 27 cm off-axis telescope and will observe ≥ 5 fields with about 12,000 stars during 5 months each. It can detect planets with $R_{pl} \geq 2\ R_{Earth}$ and orbital periods ≤ 50 days. As soon as 2008-2009, COROT should provide statistics on these objects and, by extrapolation, valuable tendencies on the abundance of terrestrial planets in the HZ, an important information for *Darwin*.



The COROT mission can detect hot big earths

***Kepler* (approved)**

Scheduled in 2008-2009, *Kepler* will detect terrestrial and larger planets near the HZ of stars with a wide variety of spectral types (Koch et al., 1998). Its 0.95 m diameter telescope, pointed continuously at a single field, will monitor about 100,000 main-sequence stars at few hundreds pc with the precision to detect an Earth-sized planet transiting in front of them. Over its 4 year lifetime, *Kepler* should provide the statistical abundance of the terrestrial planets that *Darwin* aims to characterize, a valuable information for optimal planning of the latter.



Kepler can detect Earth-like planets.

6.2.2. Formation Flying

The *Darwin* interferometer relies on Formation Flying (FF) technology to control the four Collector Spacecraft and one Beam Combiner. As described in section XXX-5, this strategy offers significant advantages. As with any new approach, however, it would be valuable to test it in space. Wisely, Europe has initiated several precursor missions that will demonstrate this and other key *Darwin* technologies.

PRISMA (approved)

PRISMA is a Swedish-led technology mission, which intends to demonstrate FF and rendezvous technologies. The Swedish Space Corporation is leading this effort, which is funded by Sweden, Germany, Denmark, France and Alcatel. The mission comprises two spacecraft and should be launched in autumn 2008 into a low, Sun-synchronous orbit (600-1000 km) with a mission lifetime of about 8 months. The main objectives are to carry out technological flight demonstrations and manoeuvring experiments, including guidance, navigation, control, and sensor techniques (Persson and Jacobsson, 2006). The positioning of the spacecraft relies on an Alcatel relative GPS technology, which should have an accuracy of ~ 10 cm. For intra-satellite distances less than 6 m, additional optical metrology should improve this accuracy.

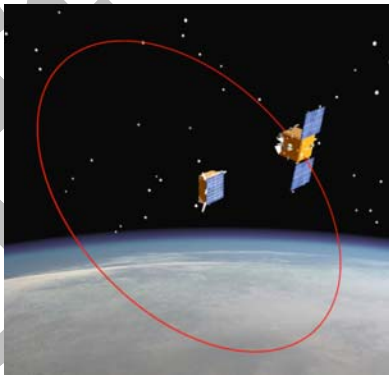


Figure XXX: Artist's rendition of PRISMA. The larger of the two spacecraft carries most of the equipment and orbits around the smaller vehicle.

PROBA 3

The PROBA-3 mission is the next logical step after PRISMA. This mission builds on PRISMA's achievements by implementing optical metrology sensors to demonstrate 30 μm relative positioning accuracy. PROBA 3 could be launched in 2010, but it is not yet fully funded. This mission is not essential for *Darwin*, but we favour its completion, because it would provide further in-space demonstration of formation flying technologies.

Pegase

Pegase is a single Bracewell interferometer that was proposed in the framework of the 2004 call by CNES for its formation flying demonstrator mission. The main scientific goal of Pegase is the high-angular resolution study of extra-solar giant planets at near-infrared wavelengths (2.5 to 5 μm). The mission could be extended to the study of brown dwarfs, circumstellar disks and dust tori around active galactic nuclei (AGN). CNES performed a Phase 0 study, but the mission was not selected for budgetary reasons. Nevertheless, the construction of a mission breadboard, called PERSEE, is under consideration to increase our understanding of nulling interferometers. Note that, in order to ensure knowledge transfer to ESA, *Pegase* is being proposed as an M mission within the Cosmic Vision programme. *An attractive possibility would be a merger with PROBA 3, with additional European and possibly international participation. This would allow the inclusion of stellar interferometry into the mission.*

7. Cost plan and International Cooperation

7.1. Cost estimate

Darwin is proposed as a L mission. ***Only a phase A study can derive a real cost estimate of Darwin***. However, a rough estimate can be useful. The proposal team gathered information from Alcatel (now Thalès Alenia Space, TAS), Astrium, and a recent study of the Emma X-array by JPL. Results are as follows.

The introduction of the Emma concept (A. Karlson, 2004 and TAS, 2006) has provided *a major simplification of the instrument*, eliminating all deployable components except the antennae. The optics of the Collecting Spacecraft (CS) are reduced to a single mirror (Sect.4). The configuration also provides *an interesting versatility*, in the sense that as the CS cost is now a sensitive function of the mirror diameter. The cost of the mission and its performance scale directly with mirror diameter. We present the costing for a 2 m version but ***the mission scope can be adjusted to the available funding***, with a corresponding change in the number of stars screened and planets with spectroscopy but at *constant quality per object* (Sect.4, and table below).

In addition, it is our hope that further simplifications can be achieved, including in the Beam Combiner Spacecraft (BCS). For example, Photonic Crystal Single Mode Fibres would support the entire 6-18 μm wavelength range with a single optical path. The current baseline splits the spectral domain since current fibres cannot operate beyond one octave of wavelengths.

Baseline Cost Items for the Emma X-array configuration with 2 m collecting mirrors.

- *Flight elements*: we use the JPL estimate of SC masses plus a 20% margin, and apply a mean cost of 220 k€ per payload kg including 15% contingencies that appears to apply to scientific payloads (Earth and astronomical observations) as well as telecommunication satellites as said by an European prime contractor. Total: 845 M€.
- *Launcher* : Ariane V ECA. 6.6 tons deliverable to L2: 125 M€ (CV Annex 4).
- *Ground Segment (5 yrs operations)*: considering the volume of communications, a prime contractor estimates 55 M€, which seems conservative when compared to that of GAIA (48 M€).
- *Pre-implementation and Space Agency internal costs*: we apply 1% and 11% of the total, respectively.

The total cost is: 845 + 125 + 55 + 12 + 128 = 1165 M€ ≈ **1200 M€**. Using a scaling laws of the collecting mirror masses with diameter $M \propto D^2$, the cost estimates in round numbers and performances, for CS mirrors from 1 to 2 m are:

Diam. (m)	M (kg)	**Total cost (M€)**	Screened stars	Planets O_3, CO_2 sp.	Planets H_2O sp.[1]
2	**3 830**	**1 200**	**218**	**49**	**(24)**
1.5	**2 960**	**950**	**142**	**32**	***(18)***
1	**2 290**	**800**	**76**	**17**	***(14)***

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[1] The method for detecting H_2O is presently under revisit, as the number of planets where this molecule can be searched for.

7.2. International Cooperation

Darwin science has worldwide appeal. At present, both *NASA* and the Japan space agency, *JAXA*, have indicated their interest in the mission and their willingness to participate in the study phase. The attached letters of intent also indicate an interest in the construction and operation phases. Additional contacts are being cultivated.

8. Public Outreach

Darwin science transcends the narrow interest of typical scientific enquiry. When the mission succeeds in identifying another world like our own, simply everything will change, from science to politics to religion. Needless to say, this type of investigation has a profound appeal to the general public. As a result, *Darwin* has both the opportunity and responsibility to support a significant public outreach programme throughout all phases of the mission.

8.1. Pre-Launch Activities

Darwin scientists have already been involved in outreach activities, including:

- Interviews and articles in newspapers and magazines: several hundred in Europe, as well as Russia, Canada and the USA
- Radio interviews: about 30 in Holland, Scandinavia and the UK
- Television programs and interview interviews: more than a dozen in a variety of countries. These include networks with worldwide reach, such as the BBC and the Discovery Channel.
- Public lectures: numerous presentations at universities, high schools and at the Hague Model United Nations

Additional plans include addressing school children and carefully designed exhibits in museums. For example, we foresee a touring exhibit with a theme of life in the Universe. Ideally, such an endeavour would involve ESA as a leading and/or sponsoring partner.

In combination with these exhibits, contests could be arranged, in which school classes would compete for the best original idea how to exploit *Darwin*. The winning programme would then be implemented and executed.

Numerous opportunities exist to meet the public face-to-face and to make presentations in connection with scientific meetings. This is also already happening at the regular *Darwin* - TPF conferences held alternatively in Europe and the United States. Inviting local celebrities, for example well-known scientists or astronauts, can increase the impact of these activities.

8.2. Outreach During Science Operations

As with a typical space mission, ESA together with the science team would hold regular press conferences, issue press releases, etc. Note, however, that the "images" obtained with *Darwin*, whether in the nulling or imaging mode, will not have the visual appeal of Hubble Space Telescope imagery. This calls for particular competence and skills in clarifying the impact of science results as they come in.

Presented properly, even a relatively poor image of another Earth can be transformational.

8.3. Post-mission activities

We anticipate collection of the major results and dissemination via the internet, on DVDs etc. *Darwin* is hopefully only the first of a long line of space missions that will investigate other worlds like our own. A carefully managed post-mission outreach program will ensure continued public support for exoplanet science.

9. List of Supporting Scientists

9.1. Core proposers

Astronomy: Absil O.(B) ; Beichman C. (US) ; Colangeli L. (I) ; Coudé du F. V. (F) ; Eiroa C. (Sp) ; Henning T. (G) ; Herbst T. (G) ; Kaltenegger L. (Au) ; Lawson P. (US); Léger A. (PI, F) ; Liseau R. (Swe) ; Mennesson B. (US) ; Mourard D. (F) ; Ollivier M. (F) ; Paresce F.(I); Penny A. (UK); Perrin G. (F); Queloz D. (Swz) ; Quirrenbach A. (G) ; Röttgering H. (NL) ; Rouan D. (F) ; Schneider J. (F) ; Tamura M. (Jap) ; White G. (UK) ; Johnston K. (US) ;

Planetology: Benz W. (Swz) ; Blanc M. (F) ; Lammer H. (Au), Léger A. (PI, F) ; Ollivier M. (F); Quirrenbach A. (G) ; Selsis F. (F) ; Stam D.(NL); Tinetti G. (F) ; Westall F. (F);

Biology – biosignatures : Cockell C. (UK) ; Kaltenegger L. (Au) ; Labadie L. (G) ; Léger A. (PI, F) ; Ollivier M. (F) ; Schneider J. (F) ; Selsis F. (F) ; Westall F. (F)

Instrument and data reduction scientists: Absil O.(B) ; Beichman C. (US) ; Chazelas B. (F) ; C. du Foresto V. (F) ; Defrère D. (B) ; den Herder J-W. (NL) ; Herbst T. (G) : Launhardt R. (G) ; Lawson P. (US); Lay O. (US); LeDuigou J-M. (F), Léger A. (PI, F) ; Liseau R. (Sw) ; Martin S. (US) ; Mawet D. (B) ; Mennesson B. (US), Mourard D. (F) ; Ollivier M. (F) ; Perrin G. (F); Queloz D. (Swz) ; Rabbia Y. (F) ; Rouan D. (F) ; Serabyn G. (US) ; Tamura M. (Jap)

9.2. Supporting proposers

Aus:

Be:

Chin:

Da:

Fin:

Fr:

Ge:

Gree:

Irl:

It:

Jap:

NL:

Nor:

Port:

Rus:

Sp:

Swe:

Swi:

UK:

USA: