6.2 Darwin

Introduction

Darwin is an ESA mission aimed at the search for, and the study of, terrestrial exoplanets orbiting nearby (< 25 pc) stars within their Habitable Zone (HZ). The mission objectives make this the most ambitious enterprise in space exploration by any space agency, especially in the technology requirements. The purpose of Darwin is two-fold. Regardless of the eventual success of occultation missions such as COROT and Kepler, Darwin will first have to perform a search for terrestrial planets orbiting nearby stars. This is because, for the occultation method to work, COROT and Kepler will observe distant stars, thereby excluding any of the Darwin target stars. Furthermore, it is physically impossible to detect Earth-size planets in the habitable zone from the ground using radial velocity techniques, because they require a precision of 0.1 m/s, much below the 0.5 m/s fundamental limit set by the acoustic noise induced by p-mode oscillations in Sun-type stars. Darwin will therefore have to find its own Earth-like planets through a survey of a pre-determined list of targets. The second, and most ambitious, objective of the mission is to study all the terrestrial planets that it finds (in our Solar System, different types of rocky worlds in the HZ are Venus, Earth and Mars, plus Mercury outside the HZ), in order to determine their physical parameters – such as orbit, temperature, evolutionary status – and to search for and analyse their atmospheres. Darwin is also designed to identify worlds on which life as we know it could exist, to search for the signature of biological activities and to perform a rough evaluation of its evolutionary status. A successful Darwin mission will therefore have a profound impact on mankind's understanding of itself, the world we live on and our place in the cosmos.

The challenge

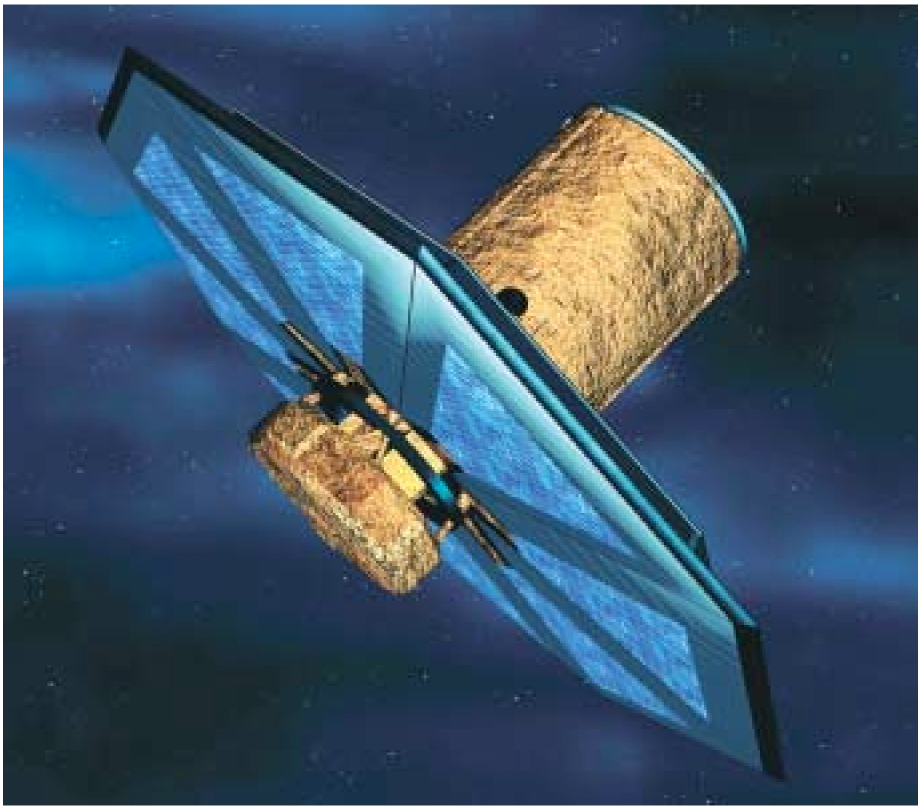
The main difficulty in detecting an Earth-size planet orbiting close enough to its star to be in the HZ is the great contrast between star and planet. A G2V Sun-type star outshines its planet by a factor $> 10^9$ in the visible and $\sim 10^6$ in the mid-IR near 10 µm. This is aggravated by the proximity of the planet to its parent star; typically 1 AU corresponds to 0.1 arcsec from a distance of 10 pc. Further, the flux of the planet is intrinsically faint and therefore demands a large collecting area.

The past 8 years have seen the field of exoplanets explode, with the discovery of more than a hundred planets within about 50 pc. All of these are, however, something more akin to Jupiter, and thus several hundred times more massive than Earth. Furthermore, these worlds often have orbits of very high eccentricities when compared to the eight major planets of our system. Lastly, owing to the selection effect, many of these exoplanets orbit very closely (a few 0.01 AU) to their parent stars, leading to the term 'Hot Jupiters'. Nevertheless, some basic facts emerge from the current set of observations: all exoplanets found so far revolve around stars of high metallicity (solar or higher); almost 15% of Sun-type stars surveyed for a sufficient time possess one or more planets; the mass function of exoplanets rises exponentially towards lower masses.

The number of detected systems is the success parameter of the mission. One may argue that detecting *one* other Earth would in itself be a major achievement. However, one of Darwin's goals is to make inferences about the origin of the Solar System, its evolutionary history and future development. This requires detection of a number of planetary systems, at least one per evolutionary stage and ideally many more. The number is currently under intense scrutiny, but a tentative baseline would be to detect and study at least 15 such systems. Assuming a random age distribution, this yields a sampling interval of 300 million years, roughly equivalent to the duration of major geological eras in Earth's history. It is not known what the prevalence, η_E, of small (0.5-2 R_E) rocky bodies orbiting other Sun-like stars is. To date, about 3000 stars have

For further information, see http://sci.esa.int/darwin

Figure 6.2.1. Artist's impression of one of the individual telescopes in the free-flying Darwin array. The warm electronics and the spacecraft bus are below the passive cooling shield. The solar arrays are also mounted on the sunward side.



been monitored with radial velocity techniques, resulting in the detection of about 120 planets, with masses of between 0.12 M_{Jup} and ~10 M_{Jup} (40-3180 M_E). An Earth-like or rocky planet is expected to have a mass below 10 M_E. Admittedly, the current searches are biased towards large planets and short orbital periods. The latter bias is, however, being remedied as time passes. Nevertheless, despite the fact that several stars have now been under continuous surveillance for more than 10 years, not a single planetary system analogue to ours has been found so far. The prevalence of Earth-like planets thus remains very uncertain but the current best guess puts it at $1 < \eta_E < 10\%$. We therefore need to survey at least 150 stars to be able to detect between 1.5 and 15 planets.

A major goal of the mission is not only to detect terrestrial exoplanets, but also to investigate if the conditions on the planets would allow life as we know it to exist – and possibly to detect its presence. The simultaneous detection of water and molecular oxygen at a temperature of about 300K would be a clear indication of life. This is because oxygen is one of the most reactive substances. If all life on the Earth were removed suddenly, all of the free oxygen in the atmosphere would disappear in the geologically short time of 4 million years. The atmosphere is out of equilibrium, as evidenced by comparison with models or with the other terrestrial planets in the Solar System (Mars and Venus). This disequilibrium is caused by the living things on Earth. Previous to this era, our biosphere was dominated by oxygen-generating species; the atmosphere of the early Earth was out of equilibrium in methane. Other molecules, such as ozone and carbon dioxide, are also good tracers of biological activities.

Technology

There are basically two types of design that would allow the detection of a faint planet close to a star that is at least a million times brighter. The first is visual coronography using a single telescope that must be at least 10 m in diameter. The second solution employs the new technology of nulling interferometry. This was selected as the baseline design for Darwin and an ambitious technology development and verification programme has been initiated.

Nulling interferometry can be described by considering two apertures, separated by a baseline D, pointing at the same star. If the optical path lengths from both apertures are the same, the amplitudes of the light outputs will interfere when they are combined. This is interferometry in the classical sense, producing dark and bright bands known as fringes. If instead the light from one of the telescopes is made to arrive at the site of beam combination with an added phase shift, π, the light along the optical axis will instead interfere destructively (the dark fringes appear 'on top' of the star). At the same time, waves arriving from a small angle θ away will interfere constructively; the separation θ depends on the distance between the two telescopes. So if a star is orbited by a planet at an angle θ away, the light from the star is extinguished and the planetary light is highlighted. The contrast between the star and planet is restricted to light leaks from the 'central null' owing to imperfections in the optics and the jitter of mechanical components. By using more telescopes it is possible to create a more complex transmission pattern. The actual pattern depends on the number of apertures, and the geometrical configuration. The Darwin baseline configuration consists of six telescopes in a hexagonal pattern, with all telescopes equidistant from a seventh spacecraft acting as the central beam combiner. Then the pattern is roughly doughnut-shaped. It is possible to tune the array to each individual star that is observed, such that the transmission ring sits on top of the habitable zone. The signal also needs to be modulated, in order to separate out the desired signal from other sources, such as exozodiacal light, and to discriminate between different combinations of planets in the observed system. This can be performed either by rotating the array of telescopes, switching between different combinations of apertures, or by a combination of both. The latter option is chosen as the baseline for Darwin. The minimum diameter of the array is $D = 40$ m and the maximum is 250 m. A separate eighth spacecraft carries the systems required for metrology, array control and communication. The eight spacecraft orbit around the Sun-Earth L2 Lagrangian point, where there is a favourable thermal environment and low level of background light. To reduce costs, studies are investigating arrays with fewer apertures. Currently, a system consisting of three spacecraft, including a beam combiner collocated with one of the telescopes and excluding the command and control satellite, is showing great promise.

To achieve its goal of investigating the physical parameters (density, pressure, temperature profile, …) and chemical composition of the planetary atmosphere, with a particular emphasis on biomarkers such as water, oxygen, ozone, carbon dioxide and methane, Darwin must operate in the wavelength range 6.5-18 µm and have a spectral resolution of at least 20.

Future

Because of its cost, Darwin will most likely be an international endeavour. Collaboration has begun with NASA's equivalent Terrestrial Planet Finder (TPF). A Letter of Agreement has been signed between ESA and NASA for 2003-2006. The NASA TPF Science Working Group and the ESA Terrestrial Exoplanets Science Advisory Team are mandated to define and agree on a common set of detailed scientific objectives by 2006. These objectives will in turn serve as a basis to define the exact design of the mission in 2007. Darwin itself is projected for a launch not earlier than 2015.