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The Darwin-GENIE Experiment: An ESA-ESO Partnership

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Abstract. Darwin is one of the most challenging space projects ever considered by the European Space Agency (ESA). Its principal objectives are to detect Earth-like planets around nearby stars and to characterize their atmospheres. Within the framework of the Darwin program, ESA and the European Southern Observatory (ESO) intend to build a ground-based technology demonstrator called Darwin-GENIE. Such a demonstrator built around the Very Large Telescope Interferometer (VLTI) in Paranal (Chile) will test some of the key technologies required for the Darwin Infrared Space Interferometer. The paper describes the objectives of the Darwin-GENIE project.

1. Introduction

Understanding the principles and processes that generated the Earth, and allowed the evolution of life forms to take place is a major scientific objective which deserves the utmost attention. In particular, the successful detection of Earth-like planets possessing environments benign to life would answer central questions such as "How unique is the Earth as a planet?" and "How unique is life in the Universe?". To achieve these objectives, the IRSI-Darwin mission of the European Space Agency (Fridlund 2000, 2002) will survey a large sample of nearby stars and search for Earth-size planets within their "habitable zone". IRSI-Darwin will measure their spectra in order to infer the presence of an atmosphere and search for the presence of biomarkers.

Detection of Earth-size bodies circling nearby stars is extremely difficult because of the weakness of the planetary signal emitted within a fraction of an arcsecond from an overwhelmingly bright star. A solar type star outshines an Earth size planet by a factor of more than 10^9 in the visible wavelength range. In the infrared spectral range, where the planet's thermal emission increases and the star's emission decreases, the contrast is still higher than 10^6. Only the planetary signal, a millionth of the stellar light, should remain in the input feed of a spectrograph in order to register a planet spectrum in a reasonable time. To accomplish such an extinguishing of light at the relevant spatial scales, the technique of "nulling interferometry" has been selected for IRSI-Darwin. By applying suitable phase shifts between different telescopes in an interferometric array, destructive interference can be achieved on the optical axis of the

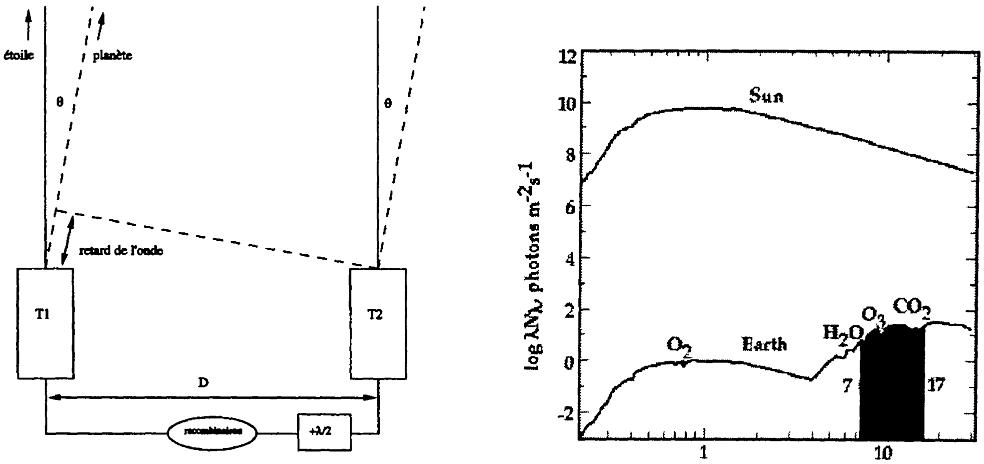

Figure 1. *Left*: Principle of a two-telescope Bracewell interferometer. *Right*: Contrast between the solar flux and the Earth as a function of wavelength in microns. Adapted from Angel et al. (1986).

system in the combined beam while interference is constructive for small off-axis angles. The principle of nulling interferometry for a simple two-telescope Bracewell interferometer (Bracewell 1978) is described in Figure 1. The equivalent transmission map of the nulling interferometer is a set of interference peaks with a sharp null in the center. By placing the central star under this null, and adjusting the interferometer baseline to the required angular resolution, planets can be detected in the "habitable zone". The actual shape and transmission properties of the pattern around the central null depend on the configuration and the distance between the telescopes.

2. The IRSI-Darwin Development Program

To date, the IRSI-Darwin mission concept (see Figure 2) consists of six 1.5 m telescopes, each of which is a free flying spacecraft transmitting its light to a central beam-combining unit (see ESA-SCI/2000/12, 2000). Using the nulling interferometry technique, the beam combiner could detect and analyze the light from Earth-like planets at distances of up to 25 parsecs. The mission concept is based on the ability to co-phase telescopes on independent spacecraft to an accuracy better than 20 nm and to perform nulling interferometry with a rejection factor of $\approx 10^6$ in a wide spectral band extending from 5 to 18 μm. In-orbit co-phasing of the free-flying telescopes could be performed in successive steps combining first a local radio-frequency positioning system with milli-Newton propulsion devices, then inter-satellite laser metrology with micro-Newton propulsion devices, and finally fringe sensors with optical delay lines. These items will be developed within the frame of the ESA Technology Research Program (TRP). They will then be tested in-orbit within the frame of the ESA Small Missions for Advanced Research in Technology (SMART) program.

In addition to the co-phasing of free-flying telescopes, a second key issue for IRSI-Darwin is the nulling interferometry technique. Hence, the TRP activi-

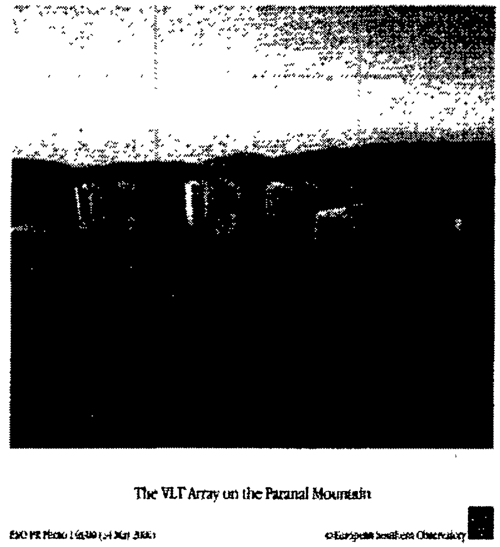

Figure 2. *Left*: Artist view of the IRSI-Darwin Space Interferometer orbiting at Sun-Earth L2 point (courtesy Alcatel Space Division). *Right*: The ESO Very Large Telescope Interferometer.

ties also include the development of Darwin specific optical components, namely achromatic phase shifters, wavefront filtering devices and infrared (IR) single mode fibers, integrated optics, IR detectors, electronics and coolers, optical delay lines and fringe sensors, as well as other components for interferometry. Laboratory nulling breadboards with star-planet simulators are currently designed that will test these components before the end of 2002. These innovative designs use the narrow telecommunication band around 1.65 μm where off-the-shelves components are available. Based on their performance, a follow-up activity has been identified that shall adapt their design to the mid-IR band and test the nulling interferometry technique on astronomical targets in IRSI-Darwin representative operating conditions.

The Very Large Telescope Interferometer (VLTI) at the ESO is the most appropriate infrastructure on the ground to perform such a test. Hence, ESA and ESO decided to initiate a definition study for a Groundbased European Nulling Interferometry Experiment which shall operate in the central laboratory of the VLTI at Mount Paranal (Chile). This experiment is called Darwin-GENIE.

3. Darwin-GENIE: A Technology Demonstrator

The primary objective of the Darwin-GENIE nulling experiment is to gain experience on the design, manufacture, and operation of a nulling interferometer using the IRSI-Darwin representative concept and technology. Nulling tests with the highest rejection factor on single stars or close binaries in broad mid-IR spectral bands will achieve this objective with the limitations imposed by the turbulence and infrared background of the Earth's atmosphere. The Darwin-GENIE experiment will combine all optical functions foreseen into the future Darwin Infrared Space Interferometer. It will benefit from the existing VLTI infrastructure, including the telescopes, the chopping schemes, the adaptive optics, the delay lines, the fringe sensors, and the beam combiner laboratory. The overall performance of the instrument will depend heavily on the performance of all VLTI subsystems and in particular on the adaptive optics and co-phasing subsystems. The GENIE optical bench within the VLTI laboratory will provide the functions specific to the nulling interferometry technique, namely photometry and amplitude control, polarization matching, phase shifting, beam combination and internal modulation, spatial filtering, spectrometry, detection, electronics, and cryogens. The detailed architecture of Darwin-GENIE will be defined during the definition study and will take into account the ESO VLTI interface characteristics and the output of the ESA TRP activities.

4. Darwin-GENIE: Preparation for the Darwin Science Program

A second objective of GENIE is to prepare the IRSI-Darwin science program through a systematic survey of IRSI-Darwin candidate targets. The solar zodiacal cloud, a sparse disk of $10-100\,\mu$m diameter silicate grains, is the most luminous component of the solar system after the Sun. Its optical depth is only $\approx 10^{-7}$, but a patch of the solar zodiacal cloud 0.3 AU across has roughly the same emitting area as an Earth-sized planet. Similar and even brighter clouds may be common in other planetary systems and may present a severe obstacle for the direct detection of extra-solar terrestrial planets. A systematic survey of IRSI-Darwin candidate targets will screen out those stars for which circumstellar dust prevents the detection of Earth-like planets. Bright exo-zodiacal clouds are easier to detect than extra-solar terrestrial planets, but finding an exo-zodiacal cloud is still difficult. The total emission from our zodiacal cloud is no more than 10^{-4} of the Sun's at any wavelength. Photometric surveys like the Infrared Astronomical Satellite (IRAS) survey can only detect exo-zodiacal clouds that are > 500 times as optically thick as the solar clouds (Backman & Parece 1993). Attempts to spatially resolve faint exo-zodiacal clouds with single-dish telescopes in the mid-infrared and near infrared (Kuchner & Brown 2000) have not yielded better detection limits.

A Bracewell interferometer using two ESO VLTI 8 m Unit Telescopes can provide better performance. However, the spatial resolution of the stellar disk by a two telescope interferometer does not allow a complete null of the starlight. Erratic fluctuations of this stellar leakage due to residuals in the control of the optical path difference (OPD) between the two arms of the interferometer are the major limitation to the achievable signal-to-noise ratio for the detection and spectroscopy of exo-zodiacal dust clouds with two VLT telescopes. The effect can be minimized by operating at long wavelengths in the N band and by using the shortest VLTI baselines (e.g., 46 or 56 meters). Assuming a conservative 20 nm OPD control accuracy, it is anticipated that an exo-zodiacal dust disk only fifteen times brighter than the solar zodiacal cloud could be detected around a G2 V star at 10 pc within 750 s. An assessment study of this scientific case for the Darwin-GENIE experiment will be further conducted, defining the analysis methods of the interferometric data that separate the circumstellar signal from the residual starlight, and inferring the morphology of circumstellar clouds.

5. Darwin-GENIE: Direct Detections of Exo-Planets?

Since 1995, more than 80 extra-solar planets have been discovered as companions to solar-type stars (Marcy, Cochran, & Mayor 2000). All of these planets were discovered indirectly in high-precision Doppler surveys. These surveys measure the radial velocity Doppler shift of the parent star due its periodic motion around the center of mass of the star plus planet system. This technique is most sensitive to massive planets with short orbital periods. The extra-solar planets that have been discovered today have mass ranges from $M \times sini \approx 0.15$ to 10 Jupiter masses (where i is the orbit inclination onto the observer line of sight) with orbital periods ranging from 3 days to a few years. Because of their proximity to the parent star ($<<1$ AU), the atmospheres of some of these planets are much hotter than that of Jupiter (and of the Earth), hence their name of hot Jupiters. With temperatures sometimes higher than 1000 K, their thermal emission is maximum in the infrared K and L bands.

With baselines ranging from 46 to 130 meters, the VLTI is optimized for the detection of planets in the L band at about 5-15 milli-arcsec from their parent star, which corresponds to 0.05-0.15 AU for a nearby star at 10 parsecs. This is especially fortunate since these planets are precisely the hot Jupiters of which a significant sample is known. The contrast between a hot Jupiter and its parent star in the L band is reduced to less than 10^4 compared to 10^6 in the N band for Earth-like planets. The starlight leakage through a two-telescope Bracewell interferometer increases as the square of the baseline and decreases as the square of the wavelength. The requirements on the OPD control accuracy between the two arms of the interferometer are slightly relaxed in the L band compared with the K band. They are within the limitation imposed by the brightness of the reference central star for nearby objects. Three-telescope configurations can in principle achieve a broader null of the star signal in the K and L bands but are not robust to residual atmospheric OPD fluctuations. Preliminary calculations indicate that a 4-VLT double-Bracewell configuration using internal modulation between two Bracewell nulling interferometers could subtract the IR background and the starlight leakage from the overall nulled signal with an accuracy sufficient to retrieve the signal from the brightest exo-Jupiters. Thus, direct detection of the hottest exoplanets might be possible on the ground using the Darwin nulling interferometry technique. The measurement of the spectrum of an extra-solar planet would be an outstanding achievement providing unique data to planetary physicist and a major step for exo-planetology.

6. Darwin-GENIE: A General User Instrument

The nulling interferometry technique in the infrared is well suited to spectroscopic studies of any faint cool object located in the immediate environment of a bright astrophysical source. A wide range of studies could potentially be conducted using the Darwin-GENIE experiment, including infrared spectroscopy of cool dwarfs in spectroscopic binaries, protoplanetary disks around T Tauri stars and Herbig Haro objects, and dust tori in the nuclei of active galaxies. Such programs will be important scientific by-products of the Darwin-GENIE experiment.

7. Conclusion

The prime objective of Darwin-GENIE is to gain experience on the design, manufacture, and operation of a nulling interferometer. The ESO Very Large Telescope Interferometer offers a unique opportunity to fulfill this objective. Secondary objectives of Darwin-GENIE are to prepare the IRSI-Darwin science program through a systematic survey of IRSI-Darwin candidate targets, to perform Darwin related science achievable from ground including spectroscopy of protoplanetary disks and low-mass companions around nearby stars, and to provide the science community with a scientifically useful instrument. ESA and ESO will initiate an initial definition study to be conducted by European industries and scientific institutes. The study will establish a preliminary design of the instrument including the specifications of its subsystems and a description of their implementation using technologies developed within the framework of the ESA Technology Research Program. Upon completion of the definition study, ESA and ESO will decide whether to proceed in the manufacturing and testing of Darwin-GENIE.

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