IRSI/Darwin: Peering Through the Interplanetary Dust Cloud

M. Landgraf, R. Jehn & W. Flury
Mission Analysis Section, ESA Directorate for Technical and Operational Support, ESOC, Darmstadt, Germany

M. Fridlund & A. Karlsson
ESA Directorate of Scientific Programmes, ESTEC, Noordwijk, The Netherlands

A. Léger
IAS/CNRS, Universite Paris XI, Orsay, France

ESA has identified interferometry as one of the major goals of the Horizon 2000+ Programme. Infrared interferometers are highly sensitive astronomical instruments that enable us to observe terrestrial planets around nearby stars. It is in this context that the infrared space-interferometry mission IRSI/Darwin is being studied. The current design calls for a constellation of six free-flying telescopes using 1.5 metre mirrors, plus one hub and one master spacecraft. As the baseline trajectory, an orbit about the second colinear libration point of the Earth–Sun system has been selected.

The thermal radiation from the interplanetary dust cloud that surrounds the Sun, the so-called 'zodiacal infrared foreground', is a major concern for any high-sensitivity infrared mission. The most reliable information about this radiation comes from the measurements made by the Cosmic Background Explorer (COBE) mission. There are various ways to detect faint terrestrial planets despite the bright foreground. We find that, using integration times in the order of 30 h, the baseline mission scenario is capable of detecting Earth-sized exo-planets out to 11 pc. Increasing the heliocentric distance of the instrument would make the observing conditions even better. A dust model that was fitted to the COBE measurements shows that an observing location for Darwin in the outer Solar System would potentially reduce the zodiacal foreground by a factor of 100, effectively increasing the number of potential target stars by almost a factor of 30.

Introduction

Since the mid-1990s the search for extra-solar, terrestrial planets (called 'exo-planets' hereafter for brevity), and the possibility of life on them has received much attention. Both ESA and NASA are studying space-based telescopes that will enable the scientific community to conduct such a search. The most promising technology that will allow the detection of exo-planets and the search for biologic activity on their surface is space-based infrared nulling interferometry. Nulling interferometry allows one to superimpose the light from a star seen from slightly different angles so that the starlight is reduced, but light from sources close to the star is enhanced. ESA is studying the Darwin infrared interferometer as a candidate Cornerstone mission. The NASA mission proposal is called the Terrestrial Planet Finder (TPF). In addition to the search for exo-planets, such interferometers could also be used for general-purpose astronomical imaging and spectroscopy with extremely high spatial resolution.

One of the main problems for the detection and analysis of Earth-sized exo-planets using an infrared telescope is the cloud of cosmic dust particles that surrounds the Sun. These dust particles are heated by the Sun and thus emit thermal radiation, called the 'zodiacal infrared radiation'. Darwin has to look through the Solar System dust cloud. Since we are looking for a planet with a peak of emission at a wavelength near the maximum of the local zodiacal foreground, we will see a considerable amount of foreground radiation. In analogy with the 'atmospheric seeing' for ground-based telescopes, which is caused by fluctuations in the Earth's atmosphere, the infrared foreground in the Solar System causes an 'interplanetary seeing'. While a constant foreground brightness can easily be subtracted from the observations, the photon noise that is generated by all light sources is a random, unpredictable brightness fluctuation. This fluctuation is proportional to the square root of the number of photons from the source. If the number of observed photons from the target exo-planet is in the order of the square root of the number of photons from the foreground, the planet's signal can no longer be clearly detected. In order to minimise the foreground, Darwin will observe mainly in the anti-Sun direction, where the zodiacal foreground is less prominent.

As a baseline, Darwin's observation window is defined to include directions less than 45° off the anti-Sun direction. But even in the anti-Sun direction, the zodiacal foreground is much brighter than an exo-planet. Since the number of collected photons increases with time, the ratio of the planet's signal to the photon noise (signal-to-noise ratio, or SNR) is proportional to the square root of the observation time. Thus, the easiest way to detect a planet behind a bright foreground is long-duration observation. Since observation time is a precious resource for a space telescope, a trade-off between observation time and other possibilities to improve the interplanetary seeing has to be made. One option is to increase the telescope's diameter. With a larger diameter the same foreground brightness is still observed, but the planet's signal is increased proportional to the area of the light-collecting surface.

Alternatively, the telescope can be placed at a larger heliocentric distance, where the infrared radiation from the dust is reduced owing to the lower interplanetary dust density and lower dust temperatures. The current baseline mission design calls for an observing location at the second co-linear Lagrangian point of the Earth–Sun system. At this point, called L2, the Earth's and the Sun's gravity plus the centrifugal force caused by the Earth's orbital motion cancel each other out. A spacecraft placed at this point will be in unstable equilibrium, i.e. it will stay there for a long time with minimum control. The advantage of putting Darwin at L2 is the relatively short distance to Earth (roughly 1.5 million km), the stable thermal environment, and the abundant availability of solar power. The zodiacal infrared foreground at 1 AU*, however, is a drawback for any highly sensitive infrared observatory at L2. It is believed that at a distance of 5 AU the interplanetary infrared foreground is less strong and becomes comparable to other sources of noise, such as light from the central star that is not perfectly cancelled.

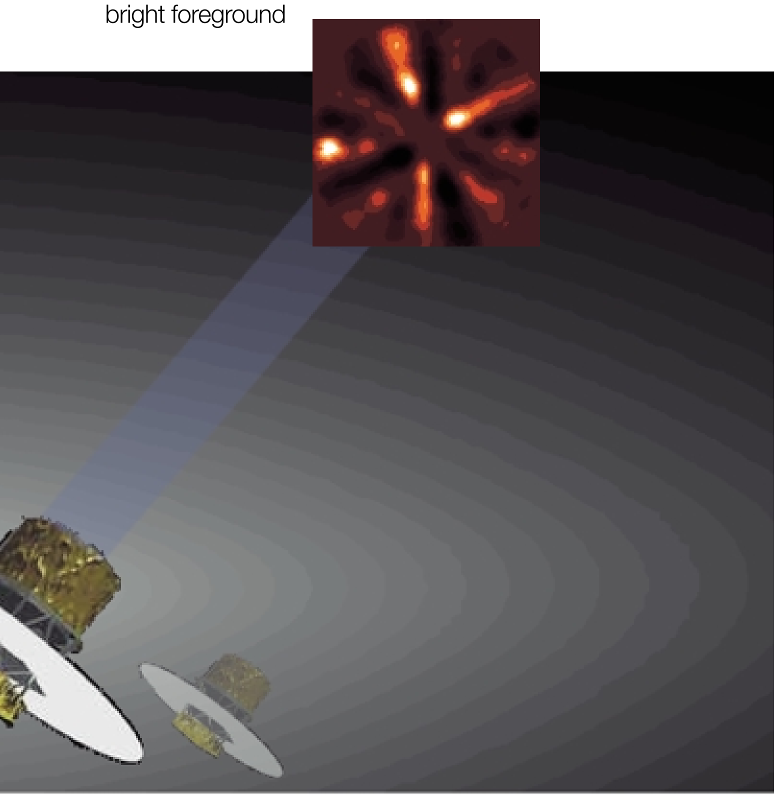

Figure 1. Darwin is surrounded by a cloud of dust that shines much brighter at infrared wavelengths than the extra-solar planets it is designed to look for

Because dust in the Solar System is mainly concentrated close to the ecliptic plane of the planets, still another possibility to reduce the infrared foreground is to put the telescope in an orbit that is inclined with respect to the ecliptic plane. In such an orbit, the telescope would cross the ecliptic plane twice and reach the maximum separation from the ecliptic plane for a short time a quarter of a revolution later. The propellant allocation needed for a change in the orbital inclination is, however, quite substantial.

How much foreground radiation is expected for observations at larger distances from the Sun or with inclined orbits? So far, infrared observations have only been performed close to the Earth. The most complete and accurate survey of the sky at infrared wavelengths between 1.25 and 240 micron has been performed by the Cosmic Background Explorer (COBE) satellite. Using the data obtained by COBE, a model of the zodiacal infrared radiation has been developed that allows one to extrapolate the expected foreground radiation to larger distances and inclined orbits. One has to be careful, however, in using such an extrapolation, because it is only well constrained close to the observing location of COBE, i.e. at 1 AU distance from the Sun and in the ecliptic plane. To acquire more accurate information on the zodiacal foreground, *in-situ* measurements of the infrared radiation should be performed. Lacking data from other observing locations, we can use the extrapolation of the COBE data to estimate how much foreground radiation can be expected if Darwin is placed at solar

* 1 Astronomical Unit (AU) is equal to the distance from the Earth to the Sun

distances of 1, 3 or 5 AU, or in orbits with 30° or 60° inclination with respect to the ecliptic plane.

Interplanetary seeing as a function of selected orbit

The amount of foreground radiation received by an instrument at a given observing location depends on the direction in which the instrument is pointing. The foreground brightness measured for a given pointing direction is the sum of the emission from all dust grains that are located in the line of sight. For a pointing direction close to the Sun, for example, a strong foreground is expected, because parts of the line of sight lie within regions where the dust density as well as the dust temperature is high. The model calculations allow us to determine the expected brightness for any pointing direction, which can be expressed using two angles: the ecliptic latitude β_{ECL}, which is equal to 0° for a pointing in the ecliptic plane, and the difference of the ecliptic pointing longitude and the ecliptic longitude of the Sun position $\lambda_{ECL} - \lambda_{ECL,sun}$. On a map in the ($\lambda_{ECL} - \lambda_{ECL,sun}$, β_{ECL}) coordinate system, the Sun is located at (0°, - $\beta_{ECL,s/c}$), where $\beta_{ECL,s/c}$ is the ecliptic latitude of the observing location.

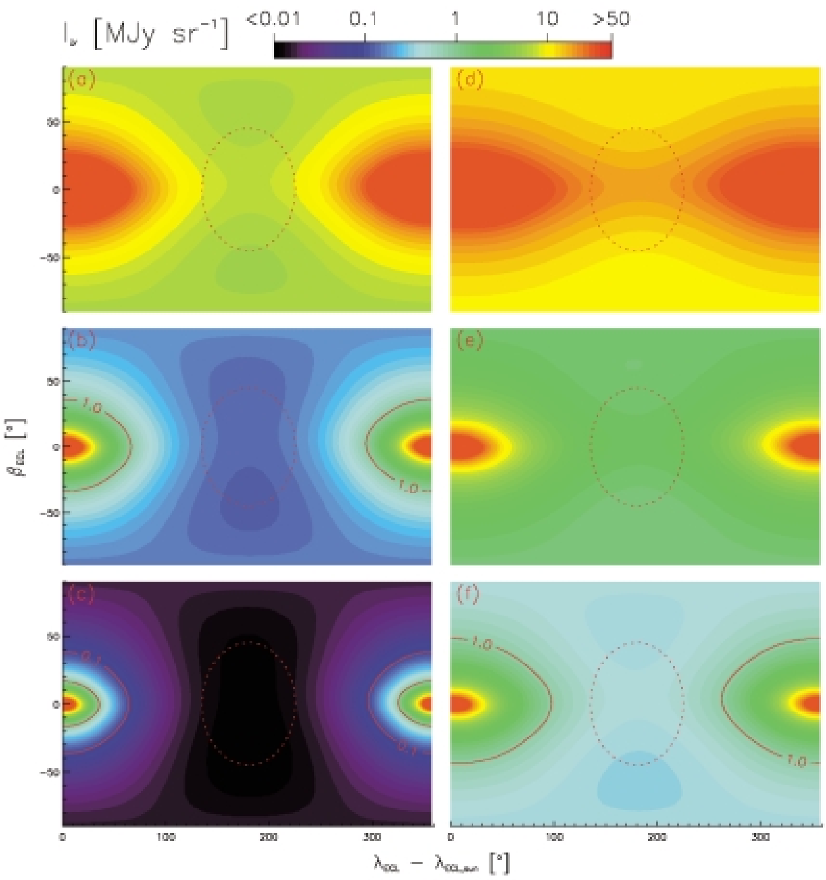

Figure 2. Sky maps of the infrared surface brightness of the interplanetary infrared foreground at wavelengths of 10 micron (a), (b), (c), and 20 micron (d), (e), (f). Panels (a) and (d) show the brightness at an in-ecliptic observing location at 1 AU, while in (b) and (e) the observation is made at a heliocentric distance of 3 AU, and panels (c) and (f) show the brightness at 5 AU. The contour lines show limiting foreground brightnesses of 0.1 and 1 MJy sr^{-1}. The dotted circle indicates Darwin's observation window within 45 deg of the anti-Sun direction

The maps of the infrared sky at wavelengths of 10 and 20 micron are shown in Figure 2, for observing locations in the plane of the ecliptic at solar distances of 1, 3, and 5 AU. It is evident from these maps that the further the telescope is located from the Sun, the *colder* the sky gets. At Earth's distance (1 AU), all of the sky is brighter than 1 MJy sr^{-1}. An improvement can be observed at 3 AU, where 84% of the sky is darker than 1.0 MJy sr^{-1} at a wavelength of 10 micron. At 20 micron, however, the whole sky is still bright. A much improved situation can be seen at a distance of 5 AU from the Sun; at the 10 micron wavelength, 96% of the sky is darker than 1.0 MJy sr^{-1}, and 83% is even darker than 0.1 MJy sr^{-1}. Also at the longer wavelength of 20 micron the foreground is reduced; 70% of the sky is darker than 1.0 MJy sr^{-1}.

It can be seen from the in-ecliptic sky maps that the infrared brightness is concentrated around the plane of the ecliptic, i.e. $\beta_{ECL} = 0$. Can the foreground be reduced by putting the telescope into an orbit that is inclined with respect to the ecliptic plane? Figure 3 shows sky maps of the expected foreground infrared brightness as seen from observing locations 30° and 60° above the plane of the ecliptic. At +30° above the ecliptic, the Sun appears at a pointing direction of β_{ECL} = -30°, as can be seen from the brightest spot in Figures 3 (a) and (c). From the maps, it is evident that at 30° the foreground is not reduced below 1.0 MJy sr^{-1} at any spot on the sky. Only at 60° above the ecliptic is the foreground reduced below 1.0 MJy sr^{-1} for 38% of the sky at a wavelength of 10 micron. Still, the sky is everywhere brighter than 0.1 MJy sr^{-1}.

Discussion and conclusion

How do we see through the interplanetary dust cloud? There is no unique answer to this question, but there are a number of options. In general the avoidance of a high foreground radiation level caused by the cloud has to be traded-off against more difficult operations, less available power, and longer transfer time to the observing location. In the current baseline mission scenario for Darwin, the zodiacal foreground is the dominant source of noise. Sufficiently long integrated observation times allow one to increase the SNR to any level required for planet detection or spectroscopy. Long observation times, however, limit the number of observations that can be performed during the mission. The advantages of the current mission design are the short transfer to the observing location (about 100 days), the spacecraft operations are straightforward, and solar power is abundantly available. The number of target stars that can be observed within the mission duration can be increased by increasing the diameter of the telescope mirrors. We find from extrapolation of the COBE results that another way to increase the number of potential targets is to increase the heliocentric distance of the instrument. While increasing the operational and transfer demands, this option would reduce the foreground level by up to three orders of magnitude. The maximum target distances for various observing locations are summarised in Table 1.

To assess quantitatively the reduction in infrared foreground for Darwin at the different observing locations, we determine the brightness $I_\upsilon^{(max)}$ of the brightest spot in Darwin's observation window (within 45° of the anti-Sun direction). As a worst-case scenario, we assume that this brightness is the infrared foreground for all observations. The results given in Table 1 have been calculated assuming a telescope diameter of 1.5 m, an Earth-sized exo-planet at 1 AU from its Sun-like central star, an observing wavelength of λ = 10 micron, an interferometric transmission of 20%, and a telescope field of view of 1.096 λ^2. Also, three different observation requirements have been considered: (a) detection of an exo-planet requires a spectral resolution of $\lambda/\Delta\lambda$ = 2 and SNR = 10, (b) spectroscopy of CO_2 features requires $\lambda/\Delta\lambda$ = 6 and an SNR = 25, and (c) spectroscopy of O_3 features requires $\lambda/\Delta\lambda$ = 20 and an SNR = 40. Requirements (a), (b), and (c) have been abbreviated as 'det.', 'CO_2', and 'O_3' in the table, respectively. For each observation requirement, we have calculated the maximum target distance for an observation time of 30 h.

From Table 1, it is evident that the baseline mission scenario is capable of exo-planet detection as well as spectroscopy of atmospheric CO_2 and O_3. Bearing in mind that already within 6.5 pc one can find more than 100 stars, it is obvious that Darwin will have a adequate number of potential targets. It is clear that the observation conditions get even better if the instrument is moved to larger distances from the Sun. Already at 3 AU, the maximum observation distance increases by a factor of three. Since the number of stars increases with the third power of the maximum observation distance, this translates into an increase in the number of potential targets by a factor of 27 ! At 5 AU, the maximum observation distance theoretically increases by another factor of 2. However, at such low zodiacal foreground levels, probably other sources of noise, like light from the central star that is not perfectly cancelled or detector noise, dominate the zodiacal foreground noise. If the zodiacal foreground was the only source of noise, O_3 spectroscopy would be possible for a target planet 25 pc away. While increasing the instrument's distance from the Sun to 3 or 5 AU would reduce the infrared foreground by more than 2 or 3 orders of magnitude, respectively, increasing the inclination of the instrument's orbit to 60 ° leads to an improvement by one order of magnitude only. Furthermore, an orbit inclination change requires more propellant than an increase in the orbit's size, effectively reducing the available payload mass. It is obviously more advantageous to increase the solar distance than the vertical distance from the ecliptic plane.

Table 1. Summary of maximum target distances for an observing time of 30 h

		$I_\nu^{(max)}$	Max. distance [pc]		
Distance [AU]	*i*	[MJy sr^{-1}]	det.	CO_2	O_3
1	0°	12	11	5.0	3.2
3	0°	0.17	33	16	9.3
5	0°	0.013	63	30	18
1	30°	5.1	14	6.8	4.0
1	60°	0.85	22	11	6.2

The uncertainty in the modelling of the interplanetary infrared foreground has been discussed in the introduction. The results presented here rely on a model of the interplanetary dust and temperature distribution that is constrained only near the Earth's orbit. A better understanding of the zodiacal foreground for Darwin is only possible if the infrared brightness is directly measured from the proposed observing locations. The advances in detector technology that allow passive cooling systems to be employed, as well as electric propulsion systems that will be flight-tested in 2002/2003 on the Smart-1 spacecraft, make a small-satellite mission equipped with an infrared camera to explore the infrared environment at 5 AU feasible. Such a precursor mission would serve two purposes: (i) it would help to make a good decision about where to put the Darwin instrument, and (ii) it would map the distribution of interplanetary dust, and thus improve our understanding of pristine Solar System material.

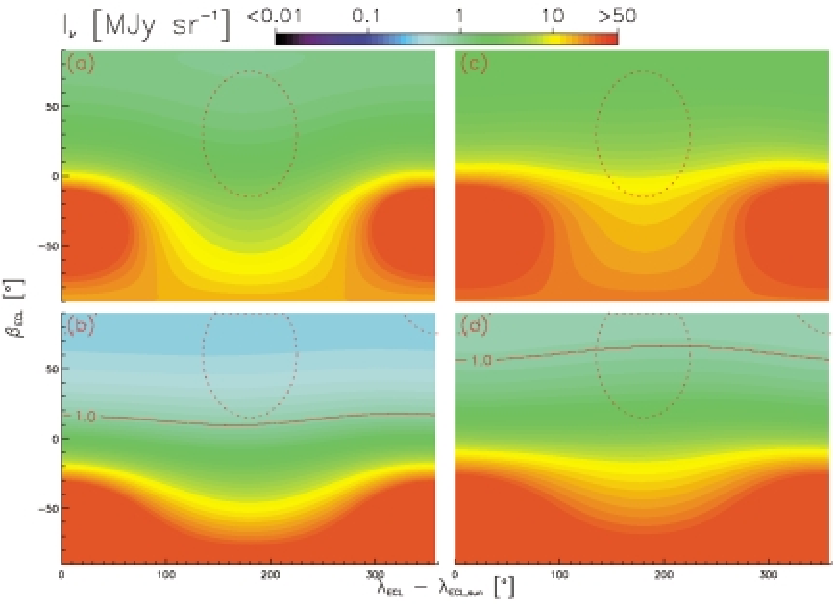

Figure 3. Sky maps of the foreground brightness of the zodiacal foreground at 10 micron (a), (b), and 20 micron (c), (d). Panels (a) and (c) show the brightness on an heliocentric orbit with 30° at a distance of 1 AU, and panels (b) and (d) show the brightness from a 60° inclined orbit also at 1 AU. The contour lines show limiting foreground brightnesses of 0.1 and 1 MJy sr^{-1}. The dotted circle indicates Darwin's observation window within 45° of the anti-Sun direction