IRSI-DARWIN: How to see through the interplanetary dust cloud

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Abstract

ESA has identified interferometry as one of the major goals of the Horizon 2000+ programme. Infrared interferometers are a highly sensitive astronomical instruments that enable us to observe terrestrial planets around nearby stars. In this context the Infrared Space Interferometry Mission (IRSI)/ DARWIN is studied. The current design calls for a constellation of 6 free flying telescopes using 1.5 m mirrors, plus one hub and one master spacecraft. As the baseline trajectory an orbit about the second collinear 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 by NASA’s 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 14 pc. We seize the suggestion that 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 of 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 (exo-planets hereafter for brevity), and the possibility of life on them has received much attention. ESA as well as 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 to superimpose the light from a star seen from slightly different angles so that the starlight is reduced, but light from possible sources close to the star is enhanced. ESA is studying an infrared interferometer named DARWIN as a candidate cornerstone mission [?]. The NASA mission proposal is called Terrestrial Planet Finder (TPF) [?]. In addition to the search for exo-planets such an interferometer 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 to 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 cannot any longer be clearly detected. In order to minimise the foreground, DARWIN will observe mainly into 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 a distant 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, SNR) is proportional to the square root of the observation time. Thus, the easiest way to detect a planet behind a bright foreground are long duration observations. 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 conceivable option is to
increase the telescopes’ diameter [?]. With a larger diameter still the same foreground brightness is 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 Lagrange 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. A spacecraft placed at this point will be in instable 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 1, however, is a draw-back for putting a highly sensitive infrared observatory at L2. It is believed that at a distance of 5 AU the interplanetary infrared foreground becomes comparable to other sources of noise, like light from the central star that is not perfectly cancelled. 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 on an orbit that is inclined with respect to the ecliptic plane. On such an orbit the telescope would cross the ecliptic plane twice and reach the maximum separation from the ecliptic plane for a short time one quarter of a revolution later. The propellant allocation needed for a change of the orbital inclination is, however, quite substantial.

How much foreground radiation is expected for observations at larger distances from the Sun or on inclined orbits? So far infrared observations have been performed only close to the Earth. The most complete and accurate survey of the sky at infrared wavelength between 1.25 and 240 µm 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 to extrapolate the expected foreground radiation to larger distances and inclined orbits. One has to be careful, however, to use 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. In lack of data from other observing locations we use the extrapolation of the COBE data, in order to estimate how much foreground radiation can be expected if DARWIN is placed at solar distances of 1, 3, or 5 AU, or on orbits with 30° or 60° inclination with respect to the ecliptic plane.

1AU: one astronomical unit equals the distance from the Earth to the Sun
Interplanetary Seeing as Function of the Selected Orbit

The amount of foreground radiation received by an instrument at a given observing location depends on the direction to 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 $\beta_{ECL}$, which is equal to $0^\circ$ 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 ($\lambda_{ECL} - \lambda_{ECL,sun}, \beta_{ECL}$) coordinate system the Sun is located at $(0^\circ, -\beta_{ECL,s/c})$, where $\beta_{ECL,s/c}$ is the ecliptic latitude of the observing location.

The maps of the infrared sky at wavelengths of 10 and 20 $\mu$m 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 the 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 are darker than 1.0 MJy sr$^{-1}$ at a wavelength of 10 $\mu$m. At 20 $\mu$m, 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 $\mu$m wavelength, 96% of the sky are darker than 1.0 MJy sr$^{-1}$, and 83% are even darker than 0.1 MJy sr$^{-1}$. Also at a longer wavelength of 20 $\mu$m the foreground is reduced: a fraction of 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. $\beta_{ECL} = 0^\circ$. Can the foreground be reduced by putting the telescope to 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 $\beta_{ECL} = -30^\circ$, as can be seen by 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 the foreground is reduced below 1.0 MJy sr$^{-1}$ for 38% of the sky at a wavelength of 10 $\mu$m. Still, the sky is everywhere brighter than 0.1 MJy sr$^{-1}$.
Discussion and Conclusion

How to 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 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 operations of the spacecraft are straight forward, 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 telescopes’ mirrors. We find from the 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. We summarise the maximum target distances for various observing locations in table 1.

In order to assess quantitatively the reduction in infrared foreground for DARWIN at the different observing locations, we determine the brightness $I_\nu^{(\text{max})}$ of the brightest spot in DARWIN’s observation window. 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 $\lambda = 10 \mu m$, an interferometric transmission of 20%, and a telescope etendue of 1.096$\lambda^2$. Also three different observation requirements have been considered: (a) detection of an exo-planet requires a spectral resolution of $\lambda/\Delta\lambda = 1$ and SNR = 10, (b) spectroscopy of CO$_2$ features requires $\lambda/\Delta\lambda = 15$ and SNR = 10, and (c) spectroscopy of O$_3$ features requires $\lambda/\Delta\lambda = 20$ and SNR = 20. Requirements (a), (b), and (c) have been abbreviated “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

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$^{2}$within 45° of the anti-Sun direction
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. But 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 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 decrease 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 of 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.

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 by SMART-1, render 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: (1) help to make a good decision where to put the DARWIN instrument, and (2) map the distribution of interplanetary dust, and thus to improve our understanding of pristine Solar System material.
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.
Figure 2: Sky maps of the infrared surface brightness $I_\nu$ of the interplanetary infrared foreground at wavelengths of 10 µm (a), (b), (c), and 20 µm (d), (e), (f). Panels (a) and (d) show the brightness at an in-ecliptic observing location at 1 AU, 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° of the anti-Sun direction.
Figure 3: Sky maps of the foreground brightness $I_\nu$ of the zodiacal foreground at 10 $\mu$m (a), (b), and 20 $\mu$m (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.
Table 1: Summary of maximum target distances for an observing time of 30 h. Other observation parameters are discussed in the text.

<table>
<thead>
<tr>
<th>dist. [AU]</th>
<th>$i$</th>
<th>$I^\text{(max)}_\nu$ [MJy sr$^{-1}$]</th>
<th>max. dist. [pc] det. CO$_2$ O$_3$</th>
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<tr>
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<td>0°</td>
<td>12.</td>
<td>14. 6.9 4.5</td>
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<td>39. 20. 13.</td>
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<td>0°</td>
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