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EXOZODIACAL DISCS WITH ALADDIN: HOW FAINT CAN WE DETECT THEM?

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Abstract. In this paper, we describe the expected performance of ALADDIN, a nulling interferometer project optimised for operation at Dome C. After reviewing the main atmospheric parameters pertaining to infrared interferometry on the high Antarctic plateau, we shortly describe the ALADDIN instrument and compute its estimated performance in terms of the smallest exozodiacal dust disc density that can be detected. Our estimations are based on a thorough end-to-end software simulator previously developed for the GENIE nulling interferometer project at VLTI. We then propose a possible mission scenario, where the southern target stars of future exo-Earth characterisation missions can be surveyed for the presence of bright exozodiacal discs (> 50 zodi) within one winter-over at Concordia.

1 Introduction

Studying the warm inner parts of debris discs—the extrasolar counterparts of the zodiacal dust cloud—is of prime importance to characterise the global architecture of planetary systems. Furthermore, the presence of large quantities of warm dust around nearby main sequence stars represents a possible threat for future space missions dedicated to the direct detection and characterisation of Earth-like planets. The occurrence of bright exozodiacal discs around solar-type stars is currently mostly unknown. As of today, exozodiacal discs have been directly resolved around a small number of main sequence stars, at a sensitivity level of about 1000 times our zodiacal dust cloud. In this context, the ALADDIN project aims at directly detecting warm dust populations around nearby main sequence stars with significantly improved sensitivity, using infrared nulling interferometry.

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In this paper, we present the main results of a thorough study of ALADDIN's estimated performance, taking into account the peculiar atmospheric conditions at Dome C and the preliminary design of the ALADDIN instrument (as described by Coudé du Foresto et al. and Barillot et al. in this volume). In light of the simulated performance and of the operation constraints at Dome C, we then discuss a possible mission scenario to survey the candidate targets of future infrared exo-Earth characterisation missions in the Southern hemisphere.

2 How faint can we detect exozodiacal discs?

To estimate the performance of the ALADDIN instrument, we have used the GENIEsim software, initially developed to simulate the performance of the GENIE nulling interferometer project at the VLTI (Absil *et al.* 2006). Thanks to the versatility of the simulator, only the input parameters had to be modified to account for the new atmospheric conditions and instrumental design. These changes are summarised in the next sections, before discussing the ALADDIN performance in terms of detectable exozodiacal disc density. We implicitly assume here that all exozodiacal discs have the same morphology as our solar zodiacal cloud, and we only scale their global density to the desired level (1 *zodi* corresponding to the density of our zodiacal cloud).

2.1 Atmospheric parameters at Dome C

In GENIEsim, the atmospheric turbulence follows the classical Kolmogorov-von Karman description under the Taylor hypothesis of frozen turbulence. The main parameters entering into the simulator are thus the Fried parameter r_0 (or equivalently the seeing) and the coherence time τ_0 (or equivalently the wind speed integrated across the whole turbulence profile). Assuming that ALADDIN observations are carried out exclusively when the instrument lies above the boundary layer where most of the turbulence is confined, we use the free atmosphere values measured by Lawrence *et al.* (2004): $r_0 = 38\,\mathrm{cm}$ (equivalent seeing of 0.27 arcsec) and $\tau_0 = 7.9\,\mathrm{msec}$ (equivalent integrated wind speed of 15 m/s).

Besides an improved atmospheric turbulence with respect to a temperate site, Dome C also offers three interesting features in the context of IR interferometry:

- An increased sky transparency, which improves and enlarges the atmospheric windows in the near- to mid-infrared;
- A reduced thermal background, from both the sky and the optical train;
- A reduced water vapour content.

In our simulations, the sky thermal background is modelled as a grey body at 230 K, with an emissivity deduced from the sky transparency ($\epsilon = 1 - \tau$). The water vapour column density is assumed to be 250 μm (as measured at South Pole), and we estimate the amplitude of its fluctuations by scaling the measurements obtained at temperate sites (see Absil *et al.* 2007 for more details).

2.2 The ALADDIN nulling interferometer concept

In view of the peculiar atmospheric properties of Dome C, we have proposed an optimised design for an Antarctic L-band Astrophysics Discovery Demonstrator for Interferometric Nulling (ALADDIN), based on a conceptual copy of the GENIE instrument. The infrastructure consists in a $\sim$ 40-m long rotating truss installed on top of a 18-m tower to reduce the effect of the turbulent ground layer, and on which are placed two moveable siderostats feeding 1-m off-axis telescopes. Thanks to the moveable siderostats, the baseline length can be optimised to the observed target, while the rotating truss allows for the baseline to be always perpendicular to the line of sight, so that neither long delay lines nor dispersion correctors are needed. Moreover, polarisation issues, which are especially harmful in nulling interferometry, are mitigated by this fully symmetric design. The available baseline lengths range from 4 to 30 m and provide a maximum angular resolution of 10 mas.

The nulling instrument works in the L band (from 3.1 to 4.1 μm) and follows the original GENIE design (Absil *et al.* 2006) adapted to the Antarctic conditions. Thanks to the low atmospheric turbulence and water vapour content, the longitudinal dispersion and intensity control loops are not needed any more, while the piston control loop can be operated at a significantly lower frequency than in the case of GENIE. The whole nulling instrument is assumed to be enclosed in a cryostat, in order to improve its overall stability and to mitigate the influence of temperature variations between seasons at the ground level. Tip-tilt closed-loop control is implemented inside the instrument to ensure a stable injection into the single-mode optical fibres.

2.3 Performance estimation

After changing the input parameters of the simulator, and disabling the dispersion and intensity control loops, we have estimated the smallest exozodiacal dust disc density that can be detected with ALADDIN in 30 min at an SNR of 5 (including the calibration of stellar leakage and background emission), for four representative targets of future space-based life-finding missions (i.e., solar type stars between 5 and 30 pc). The results are presented in Fig. 1, where the simulated performance of GENIE at Cerro Paranal is also shown for comparison. This figure illustrates that the optimum baseline for studying nearby solar-type stars is comprised between about 4 and 40 m, which closely matches the baseline range offered by ALADDIN[1]. With its 1-m class telescopes, ALADDIN significantly outperforms GENIE for the same integration time in the case of nearby targets. This fact is not only due to the exceptional atmospheric conditions, but also to the optimisation of ALADDIN both regarding the available baselines and the instrumental design. Our simulations also confirm that dispersion and intensity control are not needed, and that the fringe tracking control loop is significantly relaxed in terms of repetition

[1]Note that these optimum baselines provide an appropriate angular resolution to study the habitable zones around the target stars.

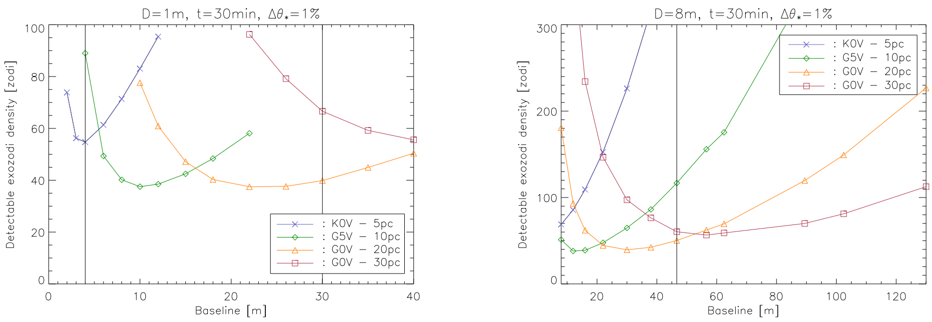

Fig. 1. Simulated performance of ALADDIN (*left*) and GENIE (*right*) in terms of the exozodiacal disc density that can be detected in 30 min of integration time for four representative targets, as a function of the interferometric baseline used. Available baselines range between 4 and 30 m for ALADDIN, and are longer than 47 m for GENIE.

frequency (about 3 kHz instead of 20 kHz in the case of GENIE). One of the most crucial points of the GENIE project is thereby mostly mitigated.

A second step was then to explore the variations of sensitivity as a function of the main input parameters of the simulation.

- *Integration time.* As for all optical interferometers, noises in ALADDIN observations come in two flavours: statistical and systematic. The effect of the statistical one decreases as the square root of the integration time, while the systematic one is not affected by the integration time. Therefore, the ALADDIN sensitivity reaches a plateau after a given time, which depends on the chosen target. For most targets in our catalogue (except the faintest ones), the sensitivity does not improve significantly after 30 min of integration. The integration time could even be reduced for the brightest targets without affecting the sensitivity.

- *Telescope diameter.* An increase in the telescope diameter has a similar effect as an increase in the integration time, except for the fact that intensity fluctuations become stronger for larger apertures. Increasing the telescope diameter beyond 2 m becomes mostly impractical as the pupil size becomes similar to the Fried parameter at the observing wavelength. 1-m class telescopes seem most appropriate to provide both a stable wavefront and a short enough integration time.

- *Boundary layer thickness.* Located 20 m above the ice, the ALADDIN telescopes have a probability of about 60% to be inside the turbulent boundary layer (Aristidi *et al.* 2009), while all the simulations performed above have been assuming that the telescopes are above the boundary layer. Therefore, we have investigated how the performance would degrade if most of the boundary layer was above the telescopes. The main effect on the performance would come from enhanced piston and intensity fluctuations. Our simulations show that a sensitivity of about 200 zodi would be reached for a G0V star at 20 pc (instead of 37 zodi in the nominal case). Ground-layer adaptive optics could significantly improve the situation, with an estimated performance of about 50 zodi for a perfectly corrected wavefront. Note that the calibration of such observations would however be severely complicated by the variability of the boundary layer strength and thickness.

3 Mission profile

The main goal of ALADDIN consists in screening the target catalogue of future exo-Earth characterisation missions to identify the stars that are surrounded by too large an amount of dust for Earth-like planet detection with these future space-based missions. In practice, exozodiacal dust densities larger than about 50 zodi cannot be tolerated for Earth-like planet characterisation (Defrère et al., in prep.). The performance of ALADDIN is well suited to identify those targets within a reasonable integration time of about 30 min. Among the target catalogue (discarding all known binary stars), about 157 stars of sufficient brightness can be observed from Dome C ($dec < -15°$). The optimum baselines for these targets have been computed, showing an almost uniform distribution between 4 and 40 m.

In theory, the total amount of time needed to observe these 157 targets only amounts to about 3.3 days, assuming a mean integration time of 30 min per target. However, in practice, all observations will need to be calibrated by observing a target with similar magnitude and colours under similar atmospheric conditions, and using a similar integration time. Furthermore, overheads need to be taken into account, including array reconfiguration, pointing, control loop initialisation, etc. Based on our experience with in-use interferometric instruments, we estimate that a total time of 2 h will then be needed for one calibrated observation. Finally, for a robust estimation of the circumstellar disc brightness, we request that three data points are obtained on each target, so that the total operating time for ALADDIN to complete the survey is about 40 days during the austral winter. Note that baselines of slightly different lengths could be used for these various observations, so as to get an additional leverage on the geometric stellar leakage, which is a known function of the baseline length. This could be used to improve the calibration of geometric stellar leakage, which is otherwise solely based on the a priori knowledge of the stellar diameter. The availability of a continuously adjustable baseline is therefore another significant advantage of ALADDIN.

In principle, the ALADDIN mission could thus be easily carried out during one single winter-over. The continuous time of good seeing 20 m above the ice might however make the situation less straightforward. Continuous periods of about 2 h would ideally be needed to carry out the core scientific programme (so that the target and calibrator can be observed successively under similar atmospheric conditions), while winter-time measurements by Aristidi *et al.* (2009) show that the mean duration of continuous good seeing (< 0.6") periods is about 45 min at 20 m. Therefore, in most cases, the calibration measurements will need to be carried out during the next period of good seeing (i.e., typically 45 min to 1 h later).

This should not be a real problem, unless the free air seeing changes drastically over periods of time of a few hours. A strategy where scientific target observations are interleaved with calibration measurements on a fixed baseline length during a few days could be appropriate in order to maximise the scientific return. Taking into account the availability of long enough periods of good seeing ($> 45\,\mathrm{min}$), two winter-overs is considered as a safe basis for the core scientific programme to be completed. Note that most of the commissioning of ALADDIN can be carried out during summertime, and that on-sky performance tests are even possible at the ground level around 17:00 each day, at the moment when the boundary layer cancels out for about 1 h. The only difference with wintertime measurements will be the higher background emission, which does not prevent from observing bright targets from our catalogue.

Although the data collected by ALADDIN should amount to about 3 Gb per hour, most of the data should be stored on site, and only small diagnostic reports need to be sent to the outside world (e.g., the Keck nulling interferometer quick look data amounts to about 20 Kb per night). The ALADDIN mission should therefore be compatible with the current Concordia bandwidth limitations. Part of the time of one scientist at the station may be devoted to the realtime monitoring of the instrument performance, although human intervention on the instrument during the wintertime is excluded.

4 Conclusion

End-to-end simulations taking into account the specific characteristics of the Antarctic environment have been carried out, showing that a nulling interferometer coupled to a pair of 1-m class telescopes in Antarctica would perform significantly better than a similar instrument working on 8-m class telescopes in a temperate site. Exozodiacal dust density levels as low as 50 times the solar zodiacal cloud are within reach around most solar-type stars within 25 pc. Such performance would bring the study of exozodiacal light to a new level, and enable a fine study of terrestrial planet environments. Within one winter-over on the high Antarctic plateau, the ALADDIN mission could identify suitable candidate targets for direct Earth-like planet detection in the Southern hemisphere, and allow to tune the design of future space missions to cope with the statistical occurrence of bright exozodiacal discs.

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