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Exoplanet science from the high Antarctic plateau

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Abstract: The Concordia station on the high Antarctic plateau has recently been realized to be the best known ground-based site for infrared interferometry, due to a combination of cold temperatures, dry air, and an atmospheric turbulence more benign than anywhere else. The maximum gains are obtained in the K and L photometric bands, and enable scientific programs (e.g., exploration of the habitable zone) otherwise only accessible from space. In the shorter term, even a simplified interferometer has potential for unique exoplanetary science.

1 Introduction

Dome C, on the high Antarctic plateau (elevation 3250 m and -75 deg latitude), is the site of the French-Italian Concordia station and a very unique environment whose main characteristics have been studied over the last few years. They are now recognized to have an exceptional potential for astronomy, most notably for high angular resolution, high dynamic range and infrared wavelengths observations:

- The ambiant temperatures ranging from 195 K (winter) to 235 K (summer), resulting in lower and more stable thermal emission from the instrument and the sky background;
- Because the air is cold, it is necessarily dry (250 μm PWV typical), improving the transmission in the infrared bands (Hidas et al. 2000). For example, the transparency window around the L band is extended from 2.8 to 4.2 μm;
- Very low surface winds: the surface winds on the Antarctic plateau are dominated by the katabatic flows of denser, colder air originating on the top of the ice cap and moving down the slopes to the edges of the continent. As Dome C is located on one of the high points in the plateau, these flows are mostly absent and the median wind speed is 2.7 m/s; and less than 5m/s more than 90 % of the time. This feature alone makes it an attractive site for extremely large telescopes (ELTs) whose large structures impose strong wind requirements to maintain operational rigidity;
- Very low free air turbulence, with a quasi-absence of high altitude jet streams as Dome C is located inside the polar vortex;

- Clear sky occurrence ≃80 %;
- An environment that provides an almost unlimited supply of flat real estate for very long baselines.

1.1 Atmospheric gains

The combination of coldness and dryness for the atmosphere results in infrared photometric gains that peak at about ×25 in the K and L bands, i.e. an antarctic 1.8 m telescope is more sensitive than an 8 m telescope on a temperate site. In the H and N bands the gain (×3) is also notable while less impressive.

With such a calm atmosphere an exceptional winter seeing was anticipated, as indeed was confirmed the teams of Nice University (Aristidi et al. 2003) and University of New South Wales (Lawrence et al. 2004): over a 3-month period, the median seeing angle was found to be 0.27 arcsec, while 0.15 arcsec was achieved more than 25 % of the time.

As most of the turbulence is located near the ground, the isoplanetic angle θ_0 is enlarged (5.9 arcsec under normalized conditions vs. 2.9 arcsec for Paranal) which improves the field of view for adaptive optics (AO). This has consequences in the feasibility of adaptive optics for ELTs where multiconjugate systems and laser guide stars may no longer be needed.

Finally, because the turbulence is generated by low-velocity winds, it is slow. There is still some debate about the normalized coherence time τ_0 (whose median value is 2.6 ms on Paranal): indirect measurements with the MASS scintillometer indicate a median value of 5.9 ms, while direct DIMM measurements show a correlation of the image motions beyond 250 ms (as would be expected from a 50 cm r_0 and a typical 2.5 m/s wind speed). Slow turbulence means better sensitivity and improved phase correction for adaptive optics systems.

1.2 Performance gains

The combination of good seeing, slow turbulence and large isoplanetic angles can be seen in two ways.

For faint sources, it results in a sensitivity improvement much beyond the ×25 factor in photometric gain. The sensitivity of adaptive optics and fringe trackers is determined by the number of photons in the coherence volume which is proportional to $r_0^2 c\tau_0$. Even taking the most pessimistic value (5.9 ms) for τ_0, that volume is increased twentifold. Compared to a temperate site, the sky coverage (likelihood of finding a reference source) at a given wavelength for cophased arrays is doubly improved by the enlarged coherence patch (in average 4 times larger than at Paranal) and the ability to seek a fainter reference. Conversely, the wavelength at which an array can be cophased with full sky coverage is moved towards the blue.

For high dynamic range observations on bright sources (coronography or nulling interferometry), the dominating sources of noise are the background fluctuations, which is reduced by the lower background level, and the residual seeing noise (phase jitter) which is reduced by the improved closed loop performance of the adaptive systems under slower fluctuations.

In the most favorable cases (K band and an L band extended to 2.8–4.2 μm) Dome C thus provides a near space quality environment at a small fraction of the access cost. The logistics for the station were developed by the French (IPEV) and Italian (PNRA) polar institutes: humans and small equipment reach the site by plane, while the heavy equipment is shipped in standard containers by boat to the coast and then by “traverses” (pack trains of caterpillar trucks) onto the glacier slopes up to Concordia.

2 Applications to exoplanet science

The quality of the site makes it possible to consider programs that would otherwise be only possible from space. In the field of exoplanets for example, it was considered that both a census of exoearths and the characterization of their atmosphere (in search for biomarkers) would require a space mission, such as ESA's Darwin (Friedlund 2004). The investigation of the habitable zone of nearby stars (the programmatically most demanding task for a space interferometer due to the reconfiguration required for each target) could very well be done earlier than expected from Dome C thanks to the extreme phase and background stability of the site. A preliminary census of exoplanets in the habitable zones would enable a space interferometer to concentrate on the spectroscopy of identified targets (at wavelengths 6–18 μm where clear biomarkers exist and which for the most part are not accessible from Dome C).

Currently, two concepts are proposed for this purpose and other astrophysical applications: KEOPS (Vakili et al. 2004), a kilometric phased array of 27 moderate size ($\simeq$2 m class) telescopes, is optimized for comprehensive (u,v) coverage and instant imaging at VLT sensitivities and ten times the nominal OWL angular resolution, while API (Swain et al. 2003), an array of a few 8 m telescopes, aims at maximum sensitivity and dynamic range. Alternatively, a 20 m monolithic telescope would have a sensitivity equivalent to a temperate OWL in the near-IR.

3 An Antarctic interferometer science demonstrator

Both KEOPS and API, or any project with a similarly ambitious goal, would be major facilities that can only be built in full international collaboration, and would exceed the current logistic resources of the Concordia station.

As a first step, and to demonstrate the science potential of the site, it appears necessary to build and operate a simple interferometer for at least one winter over. This would be used to accumulate a large database on the atmospheric turbulence parameters at Concordia and validate the implementation, commissionning and operational concepts for an antarctic stellar interferometer. Even a simple interferometer, provided that it is well optimized for its science objectives, can provide significant results in extrasolar planet research.

The Antarctic Plateau Science Demonstrator (APISD) can be defined as *the simplest form of fully operational interferometer that can provide a unique (though focused) science result in the field of exoplanet study*. Three important points need to be stressed here:

- *Fully operational*: APISD is meant to demonstrate operational concepts (fully automated observing, remote maintenance etc…) and science potential, not a specific technology. The only way to measure several atmospheric parameters relevant for long baseline interferometry, such as the outer scale of turbulence or the power spectrum of its piston mode (fringe jitter or random OPD fluctuations), is to use a two-pupil interferometer;

- *Simplicity*: in a remote site with limited support, simplicity is of paramount importance to ensure a quick success of the operation. It also makes it possible to concentrate the efforts on operational and scientific aspects, as opposed to engineering issues;

- *Focused science*: versatility (different observing modes, wavebands etc…) is a strong complexity driver for stellar interferometers. By pursuing a single and adequately chosen scientific objective it is possible to keep complexity at a strict minimum.

From all of the above it appears that the APISD has to be *single-field* (only one field of view, no use of off-axis reference star), *single-mode* (field of view limited to one Airy disk of the

Star	$M \sin i$ (M_{Jup})	P (days)	a (AU)	a (mas)	T_{eq} (K)
HD75289 (G0 V – 29 pc)	0.98	3.09	0.040	1.59	1245
HD179949 (F8 V – 27 pc)	0.42	3.51	0.046	1.48	1160
HD73256 (G8/K0 V – 37 pc	1.85	2.55	0.037	1.01	1070

Table 1: Three very southern stars (declination < -20 deg) with nearby planetary companions. The effective temperature of the planet is based on a grey body of 0.5 albedo.

individual collectors), with *naturally diffraction-limited* collectors (individual pupil size smaller than the Fried's parameter r_0 so that adaptive optics can be limited to tip-tilt correction and piston compensation). It would also feature fringe tracking capability for piston compensation. Such a platform is ideal for optimized on-axis V^2 or nulling science, and needs no sophisticated metrology.

For example, a simplified interferometer (two 1m-class telescopes) on a small baseline ($<$ 40 m) and equipped with a nulling instrument can provide the characterization of exozodys around main sequence nearby stars – a required precursor science for Darwin that otherwise necessitates massive use of UT time.

The same pair of telescopes, on longer (hectometric) baselines, but equipped with a simpler (V^2) instrument, can obtain good quality spectra of hot (Jupiter- or Neptune-class) bodies and therefore represent a major breakthrough in extrasolar planet studies. Even low-resolution ($R = 20$) spectra in the 3 to 4 μm region (L band) would enable the detection, for example, of potential CH_4 bands and provide significant information on its constituants and the amount of thermalization in the irradiated atmosphere.

Table 1 shows three very southern solar-type stars known to have a nearby planetary companion, which are observable from a site at -75 deg latitude. They are all fairly bright infrared sources with an L-band magnitude ranging between 5 and 6. With physical separations of $\simeq 0.04$ AU at 29–37 pc, the binary pairs separations range from 1.0 to 1.6 mas, within the range of the long baseline demonstrator.

4 Conclusion

The intrinsic qualities of the Dome C site for thermal infrared interferometry, which stand halfway between ground and space characteristics, make it possible to consider the implementation in a short time frame of a simplified, dedicated interferometer that would still produce unique results in extrasolar planet science. This early platform, using proven solutions in a novel environment, would demonstrate the scientific value of the Concordia station in stellar interferometry and provide the start of an upgrade path to a more ambitious facility aiming at exploring the habitable zone around nearby stars.

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