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Exoplanet detection from Dome C, Antarctica: opportunities and challenges

J. S. Lawrence, M. C. B. Ashley, M. G. Burton, and J. W. V. Storey

School of Physics, University of New South Wales, Sydney, NSW, 2052, Australia
email: jl@phys.unsw.edu.au

Abstract. Many methods have been proposed for the detection of exoplanets. The minimum detectable planetary size and mass, and the maximum distance from us at which exoplanets are observable, are determined by both technological and environmental constraints. The unique atmospheric conditions found at Dome C offer significant advantages. Using what is now known about the turbulence profile of the atmosphere above Antarctic plateau sites, we explore the potential these sites offer for detecting exoplanets around nearby stars using various methods.

Keywords. planetary systems, telescopes, instrumentation: adaptive optics, atmospheric effects, techniques: high angular resolution.

1. Introduction

The opening in 2005 of the French/Italian Concordia Station at Dome C opens new opportunities for astronomers. The combination of high altitude, low temperatures and an extremely stable atmosphere leads to major gains in sensitivity and image resolution. Previous studies at the Amundsen-Scott Station at the South Pole have shown that the infrared background on the Antarctic plateau can be as much as two orders of magnitude lower than at temperate sites, while summer-time measurements at Dome C show that the atmospheric transmission in some parts of the 10 micron window (Walden *et al.* 2005) can exceed 99.5%. Above a thin (∼36m), turbulent ground layer (Agabi *et al.* 2005; Aristidi *et al.* 2005), the atmosphere is extraordinarily stable: an average seeing of 0.27 arcseconds has been measured over a 6-week period (Lawrence *et al.* 2004). Table 1 lists relevant atmospheric parameters found at Dome C compared with South Pole and typical mid-latitude sites. Although mounting a telescope above the turbulent layer, i.e. on a 20–40 m tower or hill, may at first seem to be a difficult technological challenge, many existing telescopes at other sites are located at similar heights above ground level (e.g. the AAT at 26 m, the CFHT at 28 m, the ESO 3.6 m at 30 m, and the 4 m Mayall at 57 m).

Table 1. Atmospheric parameters relevant for exoplanet detection

Site	Seeing (arcsec)	Coherence Time (ms)	Isoplanatic Angle (arcsec)	M Band Sky Flux (Jy/as^2)	N Band Sky Flux (Jy/as^2)
Dome C	0.27[a]	7.9[a]	5.7[a]	0.5[b]	20[b]
South Pole	1.8	1.6	3.2	0.6	25
Mauna Kea	0.5	2.7	1.9	40	200
Cerro Paranal	0.8	3.3	2.6	>50	>200

[a] Mean measurements 30 m above the surface by Lawrence *et al.* 2004. Measurements by Agabi *et al.* (2005) agree with these values within uncertainties.
[b] Estimates for mid-winter, based on Walden *et al.* (2005) mid-summer measurements.

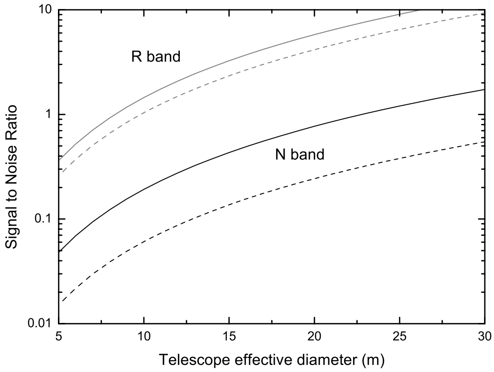

Figure 1. Photon noise limited SNR versus telescope diameter for exo-Earth detection at R (black) and N (grey) bands for Dome C (solid) and Mauna Kea (dashes) in 12 hours integration.

2. Direct Imaging

The planet-to-star flux ratio detectable with a direct imaging high-order adaptive optics coronagraphic system operating at visible or near-infrared wavelengths depends strongly on the atmospheric coherence length and coherence time. Previous models based on predictions of Dome C turbulence by Lardiere *et al.* (2004) and Angel (2003) showed large gains in the achievable SNR compared with mid-latitude sites for a given telescope size. However, recent measurements (Lawrence *et al.* 2004; Agabi *et al.* 2005) show the Dome C atmospheric coherence times may be somewhat lower than expected. Based on these measurements, Guyon (2005) has calculated photon-limited contrast ratios for Dome C and mid-latitude sites.

Provided that wavefront sensing and science imaging are performed at the same wavelength the ratio of photon-limited contrast achievable by a Dome C telescope to that of a Mauna Kea telescope is $\sim$1.9 at visible and near infrared wavelengths. This results in a relative gain in SNR of $\sim$1.4 at R band, as illustrated in Figure 1. While this is a smaller advantage than previously anticipated (Lardiere *et al.* 2004; Angel 2003), it is still significant. A Dome C telescope should be capable of imaging fainter planets around stars at greater distance than a mid-latitude system.

Direct planet imaging in the mid-infrared is limited by atmospheric emission rather than site turbulence characteristics. Although large telescopes or interferometers are required to directly image exoplanets in the mid-infrared, the advantage of Dome C relative to mid-latitude sites is much greater than in the visible or near infrared, as a result of the lower thermal sky emission (Angel 2003). For N band imaging the SNR ratio gain for Dome C relative to Mauna Kea is a factor of 3.2, as shown in Figure 1.

The simple models used for these predictions explore the fundamental limitations to direct imaging of exoplanets arising from photon noise alone. The speckle noise component of the uncorrected stellar halo will be significantly larger than the photon noise component. While techniques have been proposed to completely remove speckle noise, it is currently unknown to what extent they will be successful. Any additional contribution to the SNR from speckle noise, however, will be strongly dependent on the atmospheric characteristics, and thus it is likely that the slower turbulence observed at Dome C will be highly beneficial.

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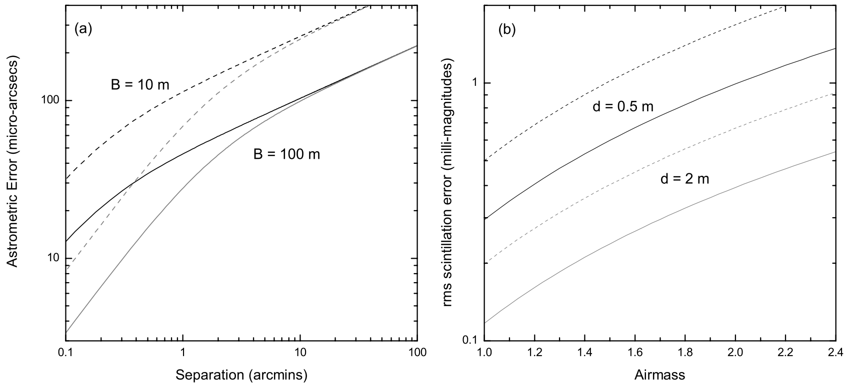

Figure 2. (a) Astrometric error versus angular separation for a 10 m (black) and 100 m (grey) baseline interferometer with a 1 hour integration at Dome C (solid) compared with Mauna Kea (dashes) (b) Scintillation-limited photometric precision as a function of airmass for 0.5 m (black) and 2 m (grey) telescopes at Dome C (solid) compared to Mauna Kea (dashes).

3. Gravitational Microlensing

The detection of exoplanets via gravitational microlensing is not fundamentally limited by any specific atmospheric characteristic or measurement accuracy. Rather, a range of optimum conditions are required to increase the detection probability. The timescale for microlensing light curves generally ranges from a few hours to a few days. Currently, telescopes at multiple sites around the world are required to examine single microlensing events. At Dome C the possibility of continuous uninterrupted observations over long time periods (hundreds of hours) with cloud free skies provides a significant advantage. In order to reduce photometric confusion from observations in crowded fields, microlensing searches require high spatial sampling with high sensitivity over large fields. The natural seeing above the boundary layer at Dome C provides higher spatial resolution than any other ground based site. Additionally, wide field adaptive optics correction at Dome C is much simpler than elsewhere due to the longer coherence time and wider isoplanatic angle.

4. Astrometry

The main limitation to exoplanet detection via ground-based narrow-angle dual beam astrometric interferometry arises from atmospheric tilt anisoplanatism. The benefits of the Antarctic atmosphere in reducing this error were examined by Lloyd *et al.* (2002), who demonstrated that the weak high-altitude turbulence observed at the South Pole should lead to an increase in astrometric precision. The weaker high-altitude turbulence observed at Dome C compared to South Pole should result in a Dome C interferometer achieving an astrometric error $\sim$40% of that achievable from most mid-latitude sites (Shao & Colavita 1992), as demonstrated in Figure 2(a). This reduction in astrometric error is unlikely to allow the detection of Earth mass planets from Dome C, as this would require the precision of 1 micro-arscec possible only from space. It will, however, lead to the capability of detecting much lower mass planets at larger distances than is possible from typical mid-latitude sites.

5. Transit searches

The fundamental limitation to the lowest planet mass detectable with a ground-based planetary transit system is atmospheric scintillation noise, which limits photometric precision to tenths of a milli-magnitude at temperate sites. The precision of ground-based systems is currently within a factor of ten of this limit. The amount of atmospheric scintillation at any site is strongly dependent on high-altitude turbulent layers. At Dome C, the high-altitude turbulence is much weaker than typically found elsewhere; this results in an improvement to the photometric precision, as shown in Figure 2(b). While the reduction in scintillation at Dome C will not be enough to achieve the ($<0.01\%$) precision necessary to detect exo-Earths, planets of significantly lower mass should be detectable than can be seen elsewhere. Additional benefits of Dome C for transit search programs include the exceptionally good clear-sky statistics, the possibility of continuous observations, a more stable point-spread function over wide fields, and lower systematic errors from airmass variations.

6. Conclusions

The Dome C site offers a number of advantages for science programs dedicated to the detection of exoplanets on telescopes of various size. The proposed 2 m aperture PILOT (Pathfinder for an International Large Optical Telescope) will be capable of transit and gravitational microlensing searches (Burton *et al.* 2005). An 8 m aperture telescope would be competitive with the next generation of mid-latitude Extremely Large Telescopes (ELTs) for much of their science, particularly in the area of infrared planet detection. Ultimately, a 25-metre telescope in Antarctica, such as Giant Magellan Telescope Antarctica (Angel *et al.* 2005) would surpass the performance of other ELTs by a wide margin.

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