DIRECT DETECTION OF SUB-STELLAR COMPANIONS WITH MIDI

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ABSTRACT

Current detection methods of planetary companions do not allow retrieving their spectral information properties. The method of Differential Interferometry has the potential to complement such information by comparing interferometric observables in various spectral channels. We outline the basic aspects of this method and how it can soon be realised by the Mid-infrared Interferometric instrument (MIDI) at the Very Large Telescope Interferometer (VLTI) observatory. A set of possible candidates for such direct observation has been selected among currently identified planetary companions. Differential Interferometry with MIDI would be complementary to other ground-based programs. The method may also be an alternative for future space-based planetary spectroscopy.

1. INTRODUCTION

For several years, the number of discovered companions has been steadily increased, mostly by studying their dynamical effects on the host star. To date, the majority of the detections use indirect methods which do not allow the spectral characterisation of the companions. In this contribution, we outline the method of Differential Interferometry, applied to gain spectral information on the companions and employing interferometric instruments offering moderate spectral resolution. One such instrument is the Mid-infrared Interferometric instrument (MIDI), which is being commissioned [1] at the Very Large Telescope Interferometer (VLTI) observatory. Together with other instruments (like, e.g., AMBER in the near-infrared), MIDI could reveal spectra of stellar companions like planets already in the medium-term range. This would complement current detection methods and therefore help prepare future, more versatile projects for observing extra-solar companions. Present developments of DI [2, 3], if confirmed by soon-to-come observations, may indeed push for a space-based use of the differential mode in combination with, or as an alternative of, the nulling technique foreseen for DARWIN.

2. INSTRUMENTATION

2.1. The Observatory

The European Southern Observatory (ESO) is currently setting up the VLTI on Mt. Paranal/Chile [4, 5]. It provides four fixed Unit Telescopes (UTs) with 8.2-m primary mirrors and eventually four movable 1.8-m Auxiliary Telescopes (ATs) which can be relocated to 30 different stations, as indicated in Fig. 1. The light from the telescopes is directed through delay line tunnels to a central laboratory. Interferometric instruments working in the near- and mid-infrared wavelength regions combine the light of two (or more) telescopes coherently. Information on the angular size of an astronomical object is contained in the fringe contrast (visibility) of the interferogram, whereas asymmetries are related to phase shifts of the interferogram.

The spatial resolution ϕ_{res} of interferometers is related to the separation B of the single telescopes (baseline) by $\phi_{res} \propto \lambda/B$. At VLTI, telescope separations of the UTs range from 47 m to 130 m and from 8 m to 202 m for the ATs. Measuring at a mid-infrared wavelength $\lambda = 10$ μm, the highest resolution with the UTs is therefore 16 mas and 10 mas for the ATs. For comparison, the red giant star α Ori (Betelgeuse, 60 pc away from Sun) shows an apparent diameter of around 55 mas in the mid-infrared [6].

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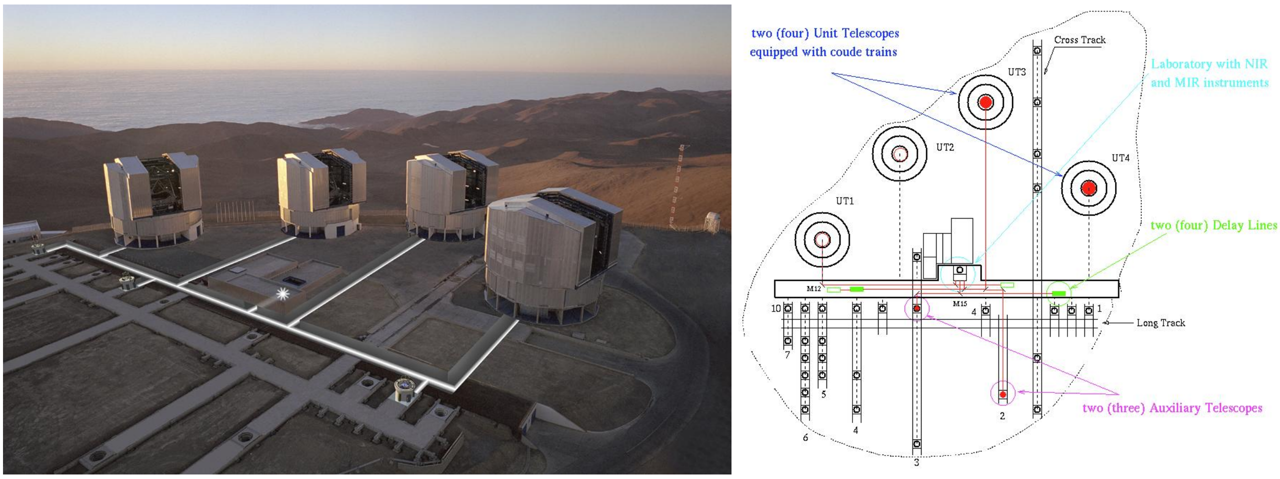

Figure 1. Aerial view and ground plan of VLTI. The aerial view shows the UTs already in place and representations of the ATs which will be installed in 2003. White lines indicate the optical path from the telescopes to the Interferometric Laboratory where the beams are combined. North is up in the layout drawing. (Images: [7])

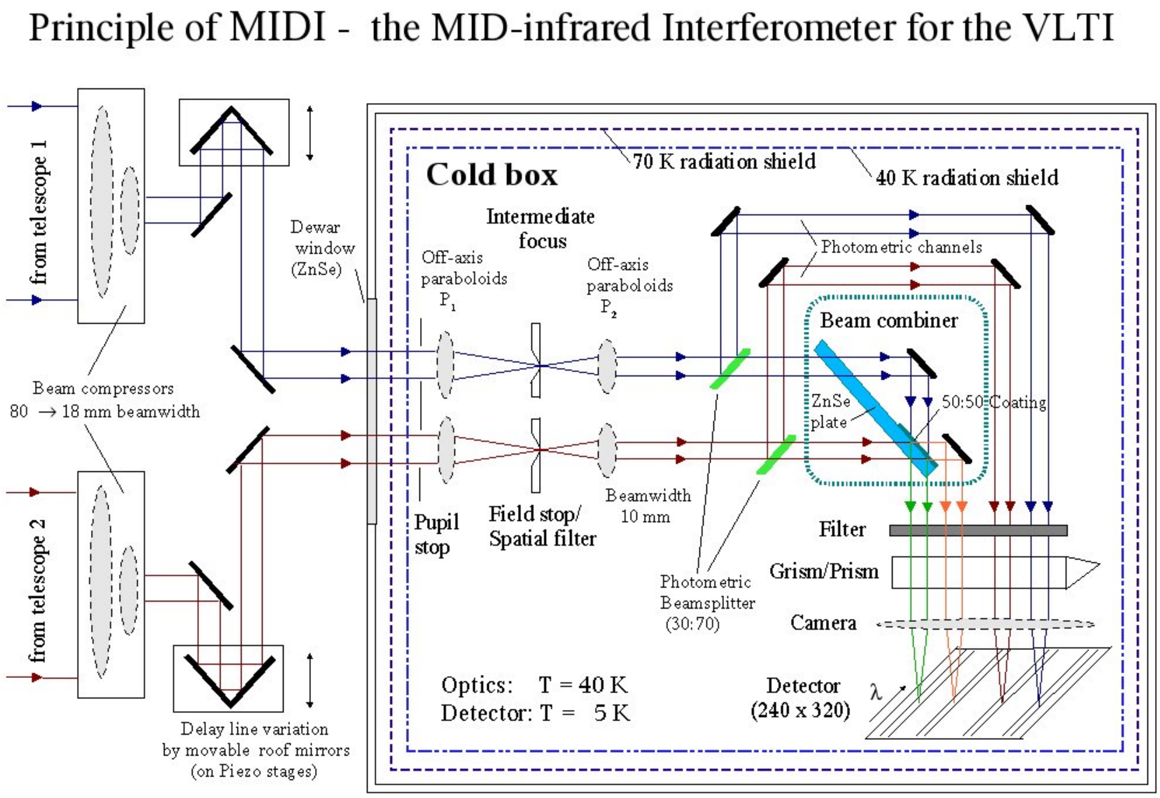

Figure 2. Scheme of MIDI. For further explanation of the instrument, refer to [1] and [8].

2.2. The MIDI Instrument

MIDI [8] is one of the interferometric instruments at the VLTI and currently in its commissioning phase [1]. It covers the N band (8...13 μm) and works as a co-axial pupil plane interferometer with two incoming beams. Different spectroscopic and photometric modes are available (see Fig. 2). In particular, MIDI provides a grism with a spectral resolution $R_g = (\lambda/\Delta\lambda) = 260$ and a prism with $R_p = 30$. Goals of limiting N magnitudes (for 10σ detections) are:

	Fringe Tracking	
Telescopes	external	self
UTs	9 mag (10 mJy)	4 mag (1 Jy)
ATs	5.8 mag (200 mJy)	0.8 mag (20 Jy)

.

Fringe tracking compensates for movements of the interference pattern due to atmospheric disturbances. At VLTI, fringe tracking will eventually be performed by FINITO or, respectively, the equivalent sub-unit of the PRIMA instrument [4, and references therein]. With the interference pattern stabilised in this way, two-beam interferometers like MIDI are able to measure both the modulus $V(B/\lambda)$ and the phase $\Phi(B/\lambda)$ (fringe contrast and fringe phase) of the complex degree of coherence of the source.

3. DETECTION OF SUB-STELLAR OBJECTS

In this section we outline a proposal prepared for guaranteed time observations with MIDI. The project is still under definition, and its feasibility will be evaluated on the basis of instrument performance as commissioning of MIDI will proceed.

3.1. Principle Idea of Differential Interferometry

Spectral dispersion of the interferometric signal in MIDI brings the possibility of direct extra-solar planet detection using Differential Interferometry (DI) [9]. For a given orbital configuration at a time t of a binary system with a period P, a dispersed interferogram contains the displacement of the photocenter dependent on wavelength. Thus, it yields both the system's angular separation and the dependence of the planet/star luminosity ratio on wavelength. DI is based on comparing measurements of visibility $V(t/P, B/\lambda)$ and/or phase $\Phi(t/P, B/\lambda)$ at different wavelengths to a reference wavelength, and so canceling all non-chromatic systematic instrumental errors. Depending on the resolution chosen for the dispersion, the measured spectral features should help constrain the parameters of radiative equilibrium of the planetary atmosphere, in particular its temperature and chemical composition.

3.2. Parameters

The theoretical limitation for DI observations is set by the fundamental noise level. For MIDI, it is mainly carried by the thermal background noise (the photon noise from the source and the read-out noise being minor contributions at 10 μm). The error of a visibility or phase measurement is a function of collecting area, spectral resolution, observing time, and brightness of the object. For example, observing a G2 star at 10 pc ($N = 2.7$) using two UTs during 3 hours and with a spectral resolution of 30 (see Sect. 2.2) yields a noise error equivalent to a phase shift of $2 \ldots 7 \cdot 10^{-4}$ rad (rms), depending on wavelength, whereas an M5 star at the same distance ($N = 6.4$) has an error of $2 \ldots 9 \cdot 10^{-3}$ rad (rms). In Fig. 3, these errors are indicated by a bold dashed line in the respective plot.

The detection potential for exo-planets appears when comparing their induced variations of the visibility or phase to the noise levels. Fig. 3 shows, as a function of wavelength, the simulated shifts of the phase Φ due to the presence of a Jupiter-size planet, as compared to the case without any companion. These displacements are plotted for two host stars of different spectral type and, in each case, for several semi-major axes of the planet orbit. Observations were considered at the maximum planet-star angular separation and with the direction of the interferometer baseline being parallel to the separation vector. We used the synthetic spectra from [10]. The applied albedo of the planet is strongly dependent on the wavelength. The planet's rotation plays a minor role in the obtained results, as does the intrinsic temperature for highly irradiated planets. The planet/star luminosity ratio, and so the interferometric signature, should grow for closer orbits and higher intrinsic temperatures of a companion (the latter depending on its mass and age). Generally, the method of DI applied with MIDI on VLTI/UTs (preferably with the longest possible baseline) potentially resolves, and allows to study, systems like 51 Peg, i.e., a Sun-like star at 10 pc and a Jupiter-like planet orbiting with a semi-major axis smaller than 0.07 AU, and possibly planetary systems around M-type stars with extremely small orbital radii. Notably, brown dwarfs are not only larger, but also have a much higher thermal emission, independent of their distance to the parent star. They are expected to be good candidates for direct detection with DI.

An additional practical limitation to the potential of detection might arise from the chromatic Optical Path Difference (OPD) between the beams, induced by dispersion in the transmissive media passed by the beams. Main sources for the chromatic OPD bias are the air in the delay line, the dioptrics of VLTI, and some possible deformation of the dispersive elements or the detector of MIDI. Since the latter, static effects can in principle be calibrated using a reference object, the relevant bias is, in fact, the evolution of the chromatic OPD with time relative to the calibration period. Reference [11] indicates a strong ef-

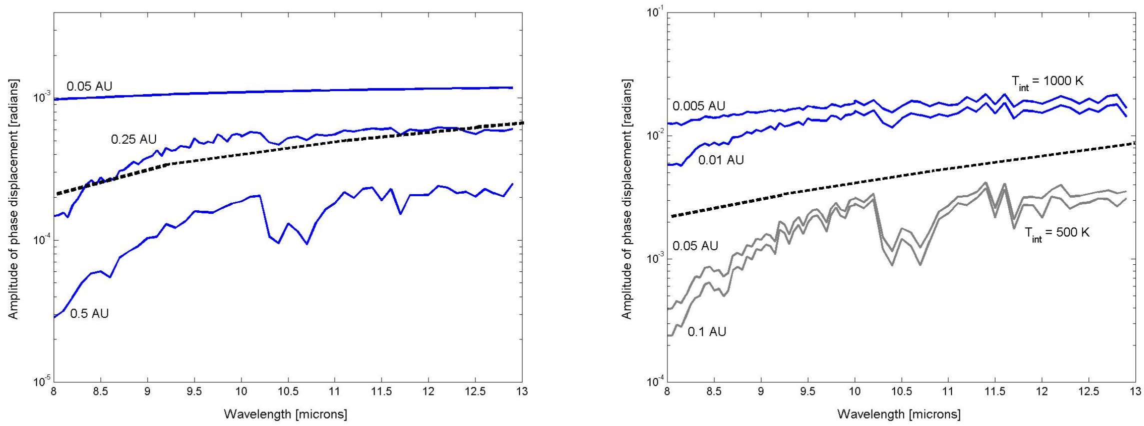

Figure 3. Expected amplitude of phase shifts with wavelength of a star + planet system located at 10 pc*, for various orbital distances. Shifts are with respect to a star without any companion. The synthetic spectrum of the planetary companion assumes a 1-Jupiter mass body and a non-dusty atmosphere (AMES-Cond simulations [10]). Noise levels (dashed lines) are for a 3-hour observation on 2 UTs with MIDI, a spectral resolution of 30, and the use of photometric channels. Left: G2 star; Right: M5 star.*

fect of dispersion in the mid-infrared and proposes solutions for at least partial correction. Estimates have been made on the amplitude and on the time constants of each of the different contributions. We anticipate that, at 10 μm, the corrected OPD effects can be lowered below the noise levels. This must imply, in particular, monitoring the dispersion due to the variable humidity in the atmosphere.

3.3. Target Selection

Candidates for the described method come mainly from radial velocity detections. The measurements provide the orbit's semi-major axis, its period and orbital phase, and a lower estimate $M \cdot \sin i$ of the companion's mass, where i is the inclination angle of the orbital plane. The behaviour of a planet's size versus its mass is highlighted, for example, in [12].

Targets suitable for MIDI must have, first of all, a sufficient overall brightness. They should be as large and as warm as possible in order to have a favourable flux ratio between star and companion. Smaller angular separations, increasing thermal emission, need to be balanced with wider separations which are better resolved by the interferometer.

4. CONCLUSIONS

Differential Interferometry appears to be a promising method to study atmospheric characteristics of 51-Peg-like planets, i.e., hot and massive extra-solar planets located closer than 0.07 AU from their star. Currently, three sub-stellar companions detected by indirect methods provide conceivable candidates for direct detection around 10 μm (GL 86, HD 112758, HD 217580). Though challenging in some instrumental aspects, and therefore feasibility needs to be evaluated along instrument commissioning, this method could be soon performed successfully with MIDI. If successful, it will be complementary to a similar DI observation program proposed with the near-infrared instrument AMBER on VLTI, which may also be performed in the near future.

In a broader perspective, the differential phase method may be foreseen for space-based applications. In the case of direct detection and spectroscopy of extra-solar planets, the space segment offers an access to the IR with considerable advantages: optimal planet/star flux ratio with low background noise and no chromatic dispersion due to the atmosphere. It may then bring a valuable alternative to nulling interferometry as a detection technique. There would be then no challenging need for stellar extinction, but it would require severe control of the chromatic OPD along the instrumental chain. Further studies would be worthwhile estimating the practical feasibility and performance of this method as a space technique.

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