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Optical techniques for direct imaging of exoplanets/Techniques optiques pour l'imagerie directe des exoplanètes

Towards the spectroscopic analysis of Earthlike planets: the DARWIN/TPF project

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Abstract

The DARWIN/TPF mission aims at detecting Earthlike planets around stars in the solar neighborhood, and determining the chemical composition of their potential atmosphere thanks to a spectral analysis of the flux from the planet itself (direct detection). Due to the large contrast between the planet and its parent star and the vicinity of these objects, high angular resolution/high dynamical range techniques are required. In this article, we describe and discuss the concept of DARWIN/TPF, a space interferometer working in a nulling mode in the thermal infrared. We describe the technological challenges required to reach the required performance, and possible ways to validate the concept, with both ground based and space demonstrators. ***To cite this article: M. Ollivier, C. R. Physique 8 (2007).***

Résumé

L'analyse spectroscopique des exoplanètes : le projet DARWIN/TPF. La mission DARWIN/TPF vise à détecter des planètes telluriques autour des étoiles du voisinage solaire et à déterminer la composition de leur atmosphère potentielle par spectroscopie du flux planétaire (détection directe). Compte-tenu du contraste entre l'étoile parente et la planète, et de la proximité des deux astres, des techniques de haute résolution angulaire et grande dynamique sont nécessaires. Dans ce texte, nous décrivons et discutons le concept de DARWIN/TPF, un interféromètre spatial fonctionnant en frange noire dans l'infrarouge thermique. Nous décrivons les défis technologiques requis pour atteindre les performances ainsi que différentes voies pour valider le concept de l'instrument, au sol comme dans l'espace. ***Pour citer cet article : M. Ollivier, C. R. Physique 8 (2007).***

Keywords: Nulling interferometry; Extrasolar planets; Infrared instrumentation

Mots-clés : Interférométrie annulante ; Planètes extrasolaires ; Instrumentation infrarouge

1. Introduction

The discovery, in 1995, of the first extrasolar planet around a solarlike star, 51 Peg (Mayor and Queloz [1]) opened a new branch of observational astrophysics: exo-planetology. Since 1995, a step by step research strategy has clearly been identified for the next decades:

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– *the search for giant planets*: this step is under way. Up to now, the development of high precision radial velocimetry has allowed the discovery of more than 200 planets with a mass between 0.017 and 21.5 Jupiter masses (Schneider [2]). With an accuracy better than 1 m/s, radial velocimetry techniques allow not only the statistical study of giant planets around nearby stars, but also the identification of several low mass objects in favorable conditions (hot planets).
– *the search for telluric planets*: the microlensing technique allowed the detection of a 5.5 Earth mass object (Beaulieu et al. [3]). Transit observation from space (COROT and KEPLER missions, see Baglin et al. [4], Borucki et al. [5]) should allow the detection and statistical analysis of a large number of telluric planets. The detection of giant and telluric planets as previously described is achievable thanks to indirect techniques of detection. The planet itself is not observed. The effect of the planet is observed on a stellar parameter (proper motion of photometry).
– *the study of planetary characteristics*: this goal can only be achieved with direct detection of the planet and spectral analysis of its flux in order to detect a potential atmosphere and characterize its composition. Such characterization can lead to the observation of bio-tracers, with the ultimate goal of finding evidence of life.

In addition to the indirect techniques, which are very successful at finding certain types of planets, direct detection techniques are under development (see this issue). The difficulty of direct detection comes both from the huge contrast between the star and the planet (typically 10^{10} in the visible spectral range and 10^7 in the thermal infrared spectral range for an Earthlike planet at 1 a.u from a solarlike star and the presence of the star in the field of view, typically at 0.1 arcsec for the same system seen 10 pc away). These constraints make the use of a space-based thermal-IR nulling interferometer a particularly attractive approach to detect and characterize Earth-like exoplanets.

2. DARWIN, TPF and nulling interferometry

The European DARWIN mission (Fig. 1) and its US homologous concept TPF (called here DARWIN/TPF) are space interferometric observatory projects working in nulling mode. They are under study respectively at ESA and NASA (Fridlund et al. [6], Beichman et al. [7]). Both concepts are based on the Bracewell nulling interferometer (Bracewell [8]).

The Bracewell nulling interferometer (Fig. 2), is made of two small separate telescopes on a rigid beam; small means here that each one cannot separate the planet from the stellar image because of the angular resolution given by

Fig. 1. Artist view of the European DARWIN observatory project (courtesy ESA).

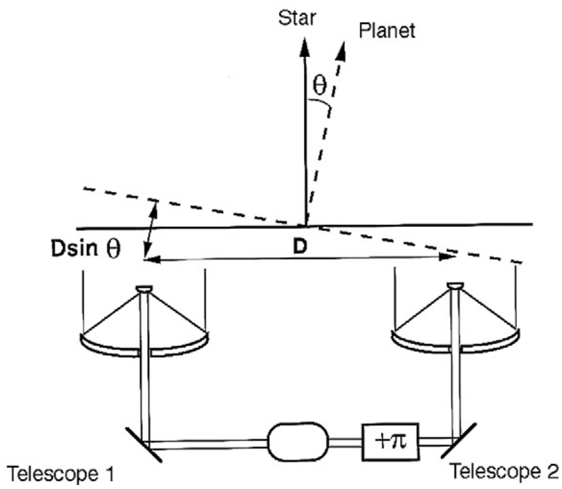

Fig. 2. Principle of the Bracewell interferometer (see the core of the text for the description of the instrument).

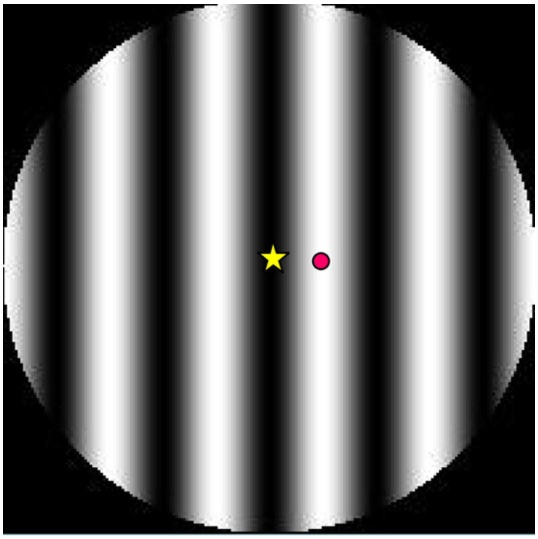

Fig. 3. Theoretical transmission of the Bracewell nulling interferometer.

the diffraction limit. The two telescopes, separated by a distance D, are both pointed towards the star. The wavefront from the star reaches the two telescopes, and if optical paths are equal, constructive interference occurs when the beams are combined. If we add an achromatic π phase shift in one arm of the instrument, interference becomes destructive on the beam combiner and the flux from the star is cancelled. Because of the small angle θ between the star and the planet, the wavefront from the planet, reaches telescope 2 before telescope 1. The time delay corresponds to an additional path of $D\sin(\theta)$. We can thus adjust D so that the additional path difference leads to a phase shift equal to $2\pi D\sin(\theta)/\lambda$ and compensates the π phase shift. We can thus get a constructive interference for the planet. The Bracewell nulling interferometer works thus as an instrument with an on-axis optical transmission of 0, and an off-axis transmission of 1 where the position of the maximum transmission can be tuned by changing the distance between the two telescopes, according to the observational wavelength λ (an optical path difference is a chromatic phase delay). The transmission of the interferometer is proportional to $\sin^2(2\pi\theta D/\lambda)$ (Fig. 3).

In order to work properly, the concept has to face several difficulties:

– the theoretical transmission is equal to zero only on-axis and varies at the first order as θ^2 off axis. Because of the angular size of the star, its flux cannot be perfectly cancelled, leading at best to a constant leakage;
– the transmission is constant in one direction. The interferometer should thus be correctly oriented to observe the planet.

That is why, in its initial version, the Bracewell nulling interferometer should be rotated. Assuming a perfect rotation and a perfect spherical star, the flux from the star (leakage) is constant while the flux from the planet is modulated according to the rotation period. The planet is detected by a lock-in detection of its modulated signal.

DARWIN/TPF concepts are a bit more complex, because they take into account other effects not considered in Bracewell's concept:

– the possible presence around the target star of an zodiacal cloud leading to an extra signal (called later exo-zodiacal light). This effect is not negligible: in our solar system, the integrated emission of the zodiacal cloud is 300 times the Earth brightness in the thermal infrared. Concepts developed to eliminate the zodiacal light effect require at least 3 telescopes.
– a rotation of the interferometer is a slow way to modulate the planetary signal and requires a permanent motion of each telescope. The DARWIN/TPF concept includes partial recombination of the beams inside sub-interferometers and internal modulation of the signal, thanks to movable mirrors (Mennesson et al. [9], Absil et al. [10]). This kind of modulation is faster and easier in term of configuration control.

Table 1
Spectral features of gaseous compounds in the thermal infrared and DARWIN/TPF detectability

Compound	Features (μm)	Spectral resolution	Terrestrial abundance	Detection threshold
NH_3	11, 10, 8.6, 5.8	10, 20, 10, 25	0.01 ppb	10 ppm
SO_2	19, 8.6, 7.7	3, 20, 25		
CH_4	8, 7.6	6, 13	2 ppm	10 ppm
N_2O	16.5, 8.6, 8	3, 20, 20	300 ppb	10 ppm
NO	5.4	50		
NO_2	6.3	30	0.1–1 ppb	100 ppb
CO	4.5	100		
O_3	9.6	17	6 ppm	1 ppm
H_2O	19, 6	3, 3	8000 ppm	1 ppm
CO_2	15	4	2 ppm	10 ppm

Table 2
Main characteristics of PEGASE's instrument and mission compared to DARWIN/TPF's requirements

Characteristic	PEGASE	DARWIN/TPF
opd control	2.5 nm rms	3 nm rms
nulling ratio	10^4	10^5
APS specification	5×10^{-3} rad	a few 10^{-3} rad
Spectral bandwidth	2.5–5 μm	7–20 μm
Baseline	20–500 m	50–500 m
Maximum angular resolution	1 mas (at 2.5 μm)	3 mas (at 7 μm)
Overall transmission (detector included)	7%	?
Spacecraft pointing	a few arcsec	?
Fine pointing	20 mas	8 mas
Fine propulsion	Improved cold gas	FEEP
Pupil size	0.3–0.4 m	1.5–3 m
Number of spacecrafts	3	4–8
Optics temperature	100 K ± 1 K	40 K
Detector temperature	55 K ± 0.1 K	10 K
Orbit	L2	L2
Launch	1 Soyouz	2 Soyouz

In such configurations, including several telescopes and internal modulation, the array should be easily configurable, with tunable baselines. Rigid links between the telescopes and the beam combiner become a strong drawback, particularly, when the distance between the telescopes has to be modified regularly. DARWIN/TPF concepts are based on free flying satellites, controlled inside a global formation. Such a configuration allows frequent reconfigurations.

Several configurations have been proposed [11–13,9], in 1-D or 2-D arrays. Other new configurations are currently under study at ESA. In any case, the goal of these studies is to define configurations that allow fast modulation capabilities, versatile reconfigurations for both nulling and imaging interferometry, simple formation setting and flying (with as few deployable parts as possible).

The technical characteristics of the instrument itself with the present level of understanding of the mission (beam combiner in nulling mode) are given in Table 2 (see Section 4).

DARWIN/TPF should work in the thermal infrared, in a spectral range between 6 and 20 μm where gaseous compounds can be identified in the potential exoplanetary atmospheres. Table 1 gives the main spectral features of gases with DARWIN/TPF detection thresholds compared to terrestrial abundances.

Several theoretical models are under development to characterize the habitability of the planet from its the spectral analysis (Selsis [14]). The idea is to get evidence of life from a low resolution spectrum of the planet. At present, the simultaneous detection of water vapor (H_2O), carbon dioxide (CO_2) and ozone (O_3) as a signature of oxygen (O_2) seems to be a strong indicator of oxygenic photosynthetic activity [14].

Because of the complexity of such missions, the project has required paper studies and technological demonstrations. As a consequence, and if the mission is selected, launch is not considered before 2025.

3. Technical requirements and laboratory demonstration of nulling interferometry

The principle of nulling interferometry is both very simple and powerful. In practice, the performance of this technique strongly depends on the efficiency of the null and its stability during the integration time. Each defect of the system can bring back on the detector the stellar photons. A modest increase in stellar light leakage can quickly decrease S/N ratio. Even in its simplest configuration (Bracewell interferometer), nulling interferometry requires tight tolerancing the quality of incoming wavefronts to be combined, in terms of amplitude, phase and polarisation at each point of the beam combiner (Ollivier [15]). Because of the large number of optical surfaces in a classical nulling interferometer beam combiner, the specific problem of polarization has been deeply studied (Chazelas et al. [16]).

It has been shown that the rigorous requirements on intensity and phase uniformity over the wavefront (typically $\Delta I/I = 10^{-3}$ and $\Delta\lambda/\lambda = 2 \times 10^{-4}$) could be relaxed by the use of optical filtering [17,18], by pinholes or better, by single mode waveguides that correct all defect orders, including tip-tilt. Specific research on single mode waveguides working in the thermal infrared is under way (Labadie et al. [19]).

In order to work on a broadband, the technique of nulling interferometry itself, requires new optical functions such as:

- phase shifters (Rabbia et al. [20]);
- beam combiners (Serabyn and Colavita [21]);
- high precision fringe sensors, connected to high accuracy delay lines;
- high rejection optical filtering;
- ...

Each sub-system should work over a large spectral range. This requires that all the subsystems are achromatic or with a very low spectral dispersion compatible with the nulling specifications.

Several laboratory test benches have been developed in the United States, France, the Netherlands and Germany, usually in the context of the ESA/NASA mission preparation. European R & D activity is mainly funded by ESA in the framework of its Technical Research program for DARWIN, and by the CNES (Centre national d'études spatiales = French Space Agency). Each laboratory bench is validating one concept or technological element:

- optical filtering by a pinhole in the thermal infrared (Ollivier [22]);
- beam combining by integrated optics in the near infrared (Weber et al. [23]);
- symmetric beam combining (Serabyn et al. [24], Flatscher et al. [25]);
- thermal infrared beam combining (Hinz et al. [26]);
- achromatic phase shifting (Branchet et al. [27], Labèque et al. [28]);
- development of thermal infrared waveguides (Labadie et al. [19]);
- ...

As mentioned before, the efficiency of the technique of nulling interferometry requires not only high rejection rates (the ratio between the stellar flux in destructive and constructive interference) but also a global stability of the interferometric extinction all over the integration time. This critical point has been addressed and is under study both theoretically and experimentally (Lay [29], Chazelas et al. [30]). This leads to new strategies to modulate the interferometric signal.

At present, the experimental benches mentioned before achieved:

- rejection rates from 10^3 to 10^5 (P. Kern: personal communication) at 10.6 μm;
- rejection rates from 10^5 to 10^7 using laser light in the visible and near infrared;
- rejection rates from 10^4 to 10^6 in the visible and the near infrared spectral range with a spectral bandwidth of about 20%;
- relative stability of 10^{-2} over several hours (Chazelas et al. [30]).

Some of the concepts used on these test benches have been proposed for ground-based astrophysical instruments. These instruments have the triple goal of:

– validating the concept in a real instrument working on the sky;
– preparing the science DARWIN/TPF should do (for instance, characterizing the environment of DARWIN/TPF targets);
– preparing the community to scientific use of nulling interferometry data.

The Keck-nuller (Serabyn et al. [31]) is at present the only existing IR-nulling instrument. Several projects have been studied, such as GENIE (Ground-based European Nulling Interferometry Experiment, Gondouin et al. [32]), a nulling instrument for the VLT-Interferometer, but the project has been given up because of the strong supplementary difficulty provided by the effects of the atmosphere and the way the VLT-I manages them (several servo loops to correct the phase fluctuations). At present, a project similar in its principle to GENIE is under study for the Franco–Italian base Concordia in Antarctica. This project, called ALADDIN, aims at building a small baseline interferometer (several tens of meters) with two 1-m class telescope to observe some of the preliminary targets of DARWIN/TPF and characterize their environment (Coudé du Foresto et al. [33]).

Considering to the efforts on both side of the Atlantic Ocean, one can guess that the global feasibility of DARWIN/TPF, at least the question of beam combination in nulling mode, will be experimentally validated at the end of 2012.

4. A DARWIN/TPF space precursor: the PEGASE project

In parallel to the laboratory work, and ground-based instruments developments to validate the concept of nulling interferometry, several space precursors have been proposed. They are called FKSI in the USA (Danchi et al. [34]) and PEGASE in Europe (Ollivier et al. [35]). Their goals are both scientific and technological and aim at preparing the observations by future exoplanet hunters such as DARWIN/TPF. They have been proposed because some of the technological aspects of DARWIN/TPF have to be tested not only from the ground but also in space (formation flying, automatic cophasing, ...).

The space mission PEGASE (Fig. 4), proposed to the CNES in 2004, in the framework of its call for scientific proposals: ‘formation flying missions’, is a 2-aperture interferometer, composed of 3 free flying satellites (2 siderostats and 1 beam combiner), allowing baselines from 50 to 500 m in both nulling and visibility modes. With an angular resolution of a few mas and a spectral resolution of several tens in the spectral range 2.5–5 microns, PEGASE has several goals:

– *science*: spectroscopy of hot jupiters (Pegasides) and brown dwarves, exploration of the inner part of protoplanetary disks and stellar environment characterisation;
– *technology*: validation in real space conditions of formation flying, nulling and visibility interferometry concepts.

PEGASE has been studied at CNES l (Le Duigou et al. [36]).

The beam combiner allows 2 types of observations on the same instrument: visibility measurements and nulling interferometry. A concept which allows simultaneously both recombination types is under study at ONERA. The

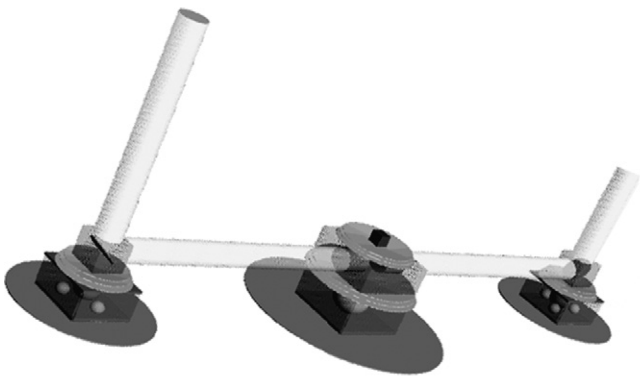

Fig. 4. Artist view of the PEGASE observatory (courtesy CNES).

main characteristics of the instrument and the mission, compared to DARWIN/TPF's requirements are summarized on Table 2. They mainly come from a trade-off study made by the CNES during the 0-level study (Le Duigou et al. [36]).

One of the particularities of the mission is that some of the requirements are spread over the satellite characteristics and the instrument itself. For instance, the global pointing is performed by the satellites themselves while the fine pointing is performed by a moving mirror on the optical path in the instrument. The cophasing of the array is performed by a global positioning of the satellite with an accuracy of 1 cm, and the action of delay lines with a stroke of 1–2 cm. The fact that some of the servo controls of the constellation are performed by the instrument itself requires a strong preliminary work in the laboratory to validate the concept.

5. Conclusions

Even if technically difficult, DARWIN/TPF is a project and concept that can allow the direct observation and the spectral analysis of terrestrial exoplanets in a near future. The following step—a resolved image of the surface (or atmosphere) of the planet—is much more complex, because the required angular resolution is at least 10^5 higher than that of DARWIN/TPF (in that case the planet is seen in a 10×10 pixels image). However, this spatial resolution requires a space interferometer with minimum baselines of 300 km, in the visible spectral range, and a huge collecting area to face the low flux. Such observatories belong the two or three next generations of space observatories.

Scientifically and technically speaking, DARWIN/TPF is thus a big step, but is certainly the only way to get detailed information on Earth-like exoplanets in the thermal infrared in the next decades.

References

[1] M. Mayor, D. Queloz, Nature 378 (1995) 355.
[2] J. Schneider, The extrasolar planet encyclopedia, http://exoplanet.eu/, 2007.
[3] J.-P. Beaulieu, et al., Nature 439 (2006) 437–440.
[4] A. Baglin, et al., ESA-SP XXX.
[5] W.J. Borucki, et al., Proc. SPIE 4854 (2003) 129–140.
[6] M. Fridlund, et al., ESA-SCI (2000) 12.
[7] C.A. Beichman, el al., JPL Publication 99-3, 1999.
[8] R.N. Bracewell, Nature 274 (1978) 780.
[9] B. Mennesson, A. Léger, M. Ollivier, Icarus 178 (2005) 570–588.
[10] O. Absil, A. Karlsson, L. Kaltenegger, Proc. SPIE 4852 (2003) 431–442.
[11] A. Léger, et al., Icarus 123 (1996) 249–255.
[12] B. Mennesson, J.-M. Mariotti, Icarus 128 (1997) 202–212.
[13] J.R.P. Angel, J.H. Burge, N.J. Woolf, Proc. SPIE 2871 (1997) 516–519.
[14] F. Selsis, A. Léger, M. Ollivier, Lecture in Astrobiology, vol. 1, Springer-Verlag, New York, 2005.
[15] M. Ollivier, in: C. Aime, R. Soummer (Eds.), Astronomy with High Contrast Imaging II, EDP Sciences, 2003, p. 235.
[16] B. Chazelas, et al., Proc. SPIE 5491 (2004) 689.
[17] M. Ollivier, J.-M. Mariotti, Appl. Opt. 36 (1997) 5340.
[18] B. Mennesson, M. Ollivier, C. Ruilier, JOSA-A 19 (2002) 596.
[19] L. Labadie, et al., Proc. SPIE 6268 (2006) 74.
[20] Y. Rabbia, J. Gay, E. Bascou, in: Proceedings of ICSO'2000, the 4th Conference on Space Optics, ed. by CNES, Toulouse, 2000.
[21] E. Serabyn, M.M. Colavita, Appl. Opt. 40 (2001) 1668.
[22] M. Ollivier, PhD Thesis, Univ. de Paris-Sud, 1999.
[23] V. Weber, et al., Proc. SPIE 5491 (2004) 842.
[24] E. Serabyn, et al., Proc. SPIE 4006 (2000) 328.
[25] R. Flatscher, Z. Sodnik, K. Ergenzinger, et al., ESA-SP 539 (2003) 283.
[26] P.M. Hinz, et al., Nature 395 (1998) 251.
[27] F. Brachet, et al., Proc. SPIE 5491 (2004) 991.
[28] A. Labèque, et al., Proc. SPIE 5491 (2004) 999.
[29] O.P. Lay, Proc. SPIE 6268 (2006) 42.
[30] B. Chazelas, et al., Appl. Opt. (2006), in press.
[31] E. Serabyn, et al., Proc. SPIE 5905 (2005) 272–283.
[32] P. Gondouin, et al., ESA-SP 539 (2003) 121–131.
[33] V. Coudé du Foresto, et al., Proc. SPIE 6268 (2006) 626810.
[34] W.C. Danchi, et al., Proc. SPIE 6268 (2006) 626820.
[35] M. Ollivier, et al., Proc. of IAU Colloq. 200 (2006) 241–245.
[36] J.-M. Le Duigou, et al., Proc. SPIE 6265 (2006) 62651M.