Direct Imaging of Exoplanets: Science & Techniques
Proceedings IAU Colloquium No. 200, 2005
C. Aime and F. Vakili, eds.

doi:10.1017/S1743921306009380

PEGASE: a DARWIN/TPF pathfinder

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Abstract. The space mission PEGASE, proposed to the CNES (Centre National d'Etudes Spatiales = French Space Agency) in the framework of its call for scientific proposals : "formation flying missions", is a 2-aperture interferometer, composed by 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
- technology : validation in real space conditions of formation flying, nulling and visibility interferometry concepts.
PEGASE has been studied at a 0-level. In this paper, we summarize the scientific program and associated technological and mission trade-off coming from this 0-level study. We also discuss how PEGASE can be considered as a TPF/DARWIN pathfinder in an international roadmap towards more complex space interferometry missions such as DARWIN/TPF.

Keywords. Interferometry, Formation flying, Spectroscopy of low mass objects, Protoplanetary disks.

1. Introduction

Both European and American space agencies plan to launch a space interferometer dedicated to the detection and analysis of extrasolar planets and particularly telluric ones, in order to determine the composition of their potential atmosphere and search for evidence of life thanks to gazeous bio-tracers identification (DARWIN and TPF projects, called in the following pages DARWIN/TPF). DARWIN/TPF is based on the nulling interferometry concept (Bracewell 1978), and consists of 3 to 6 free flying telescopes which beams are recombined on a central hub, located at a distance of a few tens of metres from each telescope (Fridlund *et al.* 2000, Beichman *et al.* 1999). The difficulty of such a mission is huge and if we except the SIM mission (astrometric interferometer), no interferometer will ever have flown at DARWIN/TPF launch epoch. In this context, a project of space interferometry precursor has been proposed to the CNES as an answer to its call for ideas on formation flying. This project is called PEGASE and has been studied at a 0-level by the CNES. PEGASE is a space 2 telescope interferometer (two 30 to 40 cm telescopes on the central hub fed by 2 siderostats on separate free flying spacecrafts) allowing baselines from 20 to 500 m. The observation spectral range goes from 2.5 to 5 μm, and the spectroscopic mode should allows spectral resolution of about 60 in the whole spectral range. We present in the next sections the main characteristics of the project.

2. PEGASE: scientific objectives

PEGASE science cases can be addressed in two categories:
- the main program : for which the instrument is particularly designed or suited,
- the secondary program : achievable only if compatible with the choices made during the instrument design phase, or using non classical ways of measurement (using the fringe sensor information for instance).

At the boundary of these two classes, several programs can be considered : the first design of the instrument and the observatory seem to make them achievable, but the demonstration has to be done. This is the case of the exoplanet zodiacal disks which are debris disks responsible for the exo-zodiacal light emission (called later "exo-zodi") study. A back of the envelop calculation of the sensitivity of the instrument lets hope the detection and measurement of exo-zodi until the limit of a few tens solar zodi level (spatially integrated emission of the Solar System zodiacal emission) around solar type stars. However, this point has still to be confirmed and won't be detailed in this paper. In this section we consider only the main program for which specific studies have been done.

The main program is made of two different scientific targets:
- the stellar, substellar and planetary companions,
- the protoplanetary disks.

The observation of stellar, substellar and planetary companions aims at providing a unified theory for the formation of these objects. In the standard model, stars form by gravitational collapse of a gas cloud, while planets form by accretion of a cloud of planetesimals. The question is to know where the limit between these two mechanisms is, and if it corresponds to the the observed "brown dwarf desert" (Marcy *et al.* 2000). Observing stellar companions (and thus gravitationally linked objects) has the advantage of giving an accurate estimation of the mass of the companion (thanks to the observation of the companion trajectory and the three Kepler's laws) and its age (thanks to the spectroscopic study of the main target) compared to free flying object where these parameters have to be estimated using theoretical models. The study of the structure and the atmosphere of all these objects (low mass stars, brown dwarfs and planets) should give a new vision of their formation and evolution. The observation of young systems helps including the time parameter in the description of these objects. Spectroscopy, even at low resolution (typically 60), is sufficient to discriminate the potential role of the clouds and aerosols in the thermalisation of the atmosphere allowing the evolution of present atmospheric models. Compared to the specific method of spectroscopy (or at least spectral band photometry) during the secondary eclipse (when the planets passes behind the star), direct observation by interferometry of the planet at different orbital phases allows observing different parts of the atmosphere and determining its thermal homogeneity (Fig. 1). The scientific programs plans the observation of 20 to 30

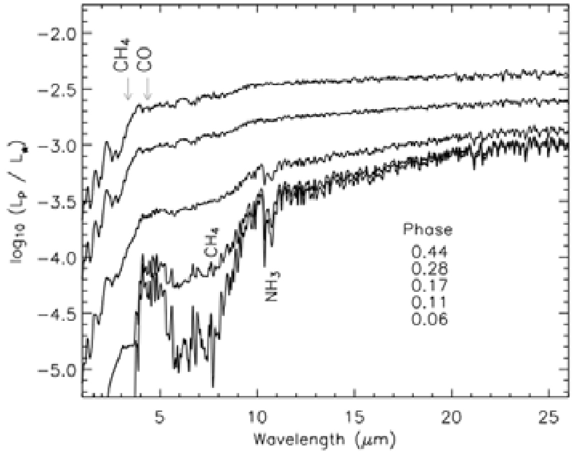

Figure 1. Planet-star flux density ratios for HD209458b at different orbital phase (from Barman *et al.* 2005).

pegasides ("hot jupiters"), and 10 to 20 brown dwarfs and low mass stars, according to their existence and observability.

The observation of protoplanetary disks in visibility mode aim at constraining the models used to describe the objects. Instead of classical visibility measurements as a function of the baseline, we suggest to measure the visibility in spectroscopic mode (as a function of the wavelength). In that observation mode, inhomogeneities in the disks (gaps for instance) appear more distinctly compared to a classical homogeneous disk (Fig. 2). Protoplanetary disks observations require however a strong effort in terms of source modeling.

With a unique observation spectral range from 2.5 to 5 μm, and effective baselines from 50 (maybe less) to 500 m, PEGASE is a unique instrument that has no equivalent on ground, particularly for Pegasides observations and spectroscopy. In addition, PEGASE, if decided, may be the first interferometer in space (SIM launch is not clear at the time these words are written).

3. PEGASE: description of the project

PEGASE is a free flying interferometer made of 3 satellites, 2 simple siderostat satellites with only propulsion, pointing, a metrology capability and a central hub, where the whole formation flying control, the beams combination, the data processing and transmissions are performed (Fig. 3).

The beam combiner allows 2 types of observations on the same instrument: visibility measurements (direct recombination) and nulling interferometry. A concept which allows simultaneously both recombination type is under study at ONERA. The main characteristics of the instrument and the mission, compared to DARWIN/TPF's requirements are summarized on table 1. They mainly come from a trade-off study made by the CNES during the 0-level study.

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

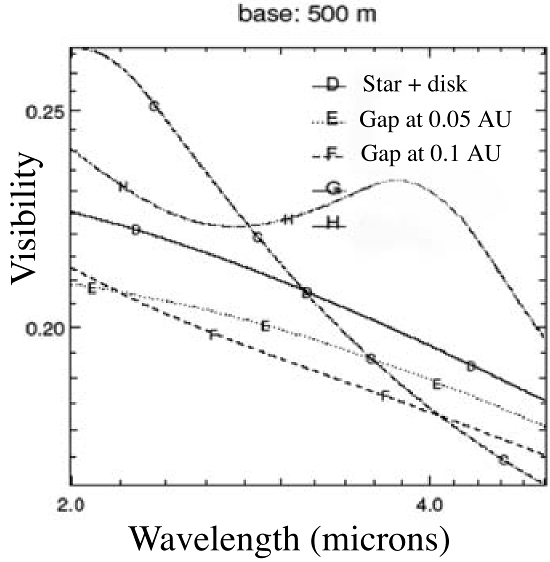

Figure 2. Visibility of a FUOr disk with a gap as the function of the observation wavelength and gap position.

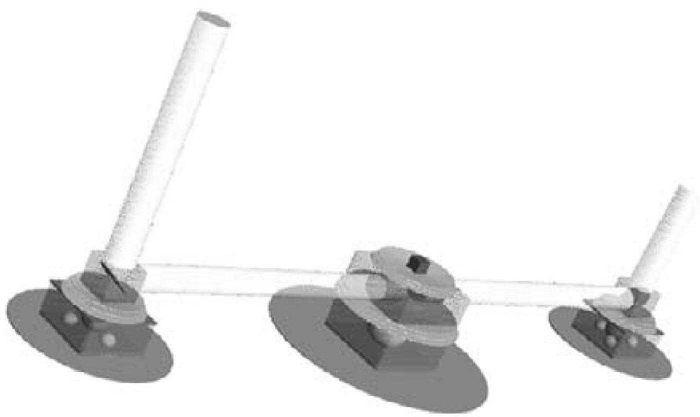

Figure 3. Artist view of the PEGASE observatory (courtesy CNES).

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.

4. PEGASE as a DARWIN pathfinder

With different science cases, and as a consequence different optical and technology requirements and reduced cost and complexity, PEGASE cannot be considered as a

Characteritic	**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 $\pm$ 1 K	40 K
Detector temperature	55 K $\pm$ 0.1 K	10 K
Orbit	L2	L2
Launch	1 Soyouz	2 Soyouz

Table 1. Main characteristics of PEGASE's instrument and mission compared to DARWIN/TPF's requirements.

light version of DARWIN, which main goal remains the observation and analysis of telluric extrasolar planets around nearby stars. However, PEGASE can be considered as a useful pathfinder because it will allow validating directly several concepts that cannot be validated from ground (high accuracy delay lines for instance cannot be tested on stellar target because of the atmosphere effects, formation flying...). In the context of a risky, expansive DARWIN concept, a mission comparable to PEGASE or a bit more ambitious project can be a first step towards the spectral characterisation of planetary companions. The keypoints of the trade-off will be :
- the kind of objects that have to be observed (and thus the sensitivity and the design of the mission)
- the spectral range and resolution at which observations are done
- the costs and time schedule of the development and building phases of the project

This point is under study in international space agencies. A collaboration process is also under discussion.

Acknowledgements

The authors would like to acknowledge all the people involved in the project on both scientific side (Co-I of the proposal and all the anonymous small hads) and technical side, mainly at CNES and Onera for the huge work done during the 0-level study in spring 2005.

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