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Pegase: a space interferometer for the spectro-photometry of Pegasides

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Abstract: Pegase is an answer to the CNES call for ideas for a scientific payload on its Formation Flying technological mission. It proposes a Bracewell interferometer operating in the infrared (1.5 – 6 μm) and visible regimes. It has small telescopes (40 cm) but a substantial baseline (25 to 500 m). Its angular resolution reaches 1 milli-arcsecond at 4 microns and 100 micro-arcsecond at 0.4 μm. Its main scientific objectives are the spectroscopic study of weak companions including Pegasides (hot giant exoplanets) and brown dwarfs bounded to other stars, with the goal to determine the composition of the atmospheres of these objects as well as their internal structure. In the present paper, we present a general overview of the science goals and the preliminary design of the instrument, and eventually give an estimate of its expected performance.

1 Introduction

The French Space Agency (CNES) is currently preparing a possible space mission for the demonstration of formation flying with two or more mini- and/or micro-satellites, with a foreseen launch between 2010 and 2012. A call for ideas for a scientific payload on board this technology demonstration mission has been issued in the beginning of 2004. This paper presents an answer to this call for ideas prepared by a group of French and European institutes, consisting in a nulling interferometer for the spectroscopic analysis of hot giant extrasolar planets (Pegasides), brown dwarfs and for various high-contrast imaging purposes. Nulling interferometry, a technique first proposed by R. Bracewell (1978) consists in coherently recombining the lights collected by two telescopes, adjusting their respective phases in order to create a destructive interference on the axis of the interferometer while letting through the close neighborhood of the central object (usually a bright star) thanks to constructive off-axis interferences. This type of instrument is particularly well suited to the study of high-contrast objects such as giant exoplanets close to their host stars. Indeed, about one quarter of the giant exoplanets detected so far have orbital distances smaller than 0.1 AU, which make their equilibrium temperature reach at least 600 K. The thermal emission of such planets is maximum in the near-infrared, a wavelength regime in which Pegase will operate (from 1.5 to about 6 μm). Brown dwarfs bounded in multiple systems are also a privileged target for such an instrument.

Besides its main scientific goals, Pegase also aims at preparing future space missions such as Darwin and TPF (detection and characterization of terrestrial extrasolar planets), but also other formation flying missions such as XEUS (X-ray telescope) or LISA (detection of gravitational waves) through the demonstration of high-precision formation flying.

2 Scientific goals

There are three main types of targets for the Pegase interferometer: hot Jupiters, brown dwarfs and circumstellar disks. The most compelling science goal, which is also the highest priory and design driver, is hot giant exoplanets.

2.1 Hot giant exoplanets (Pegasides)

Pegasides, named after the prototype and first detected 51 Peg (Mayor and Queloz 1995), designate the giant extra-solar planets of Jupiter-type mass orbiting close to their parent stars (0.02 to 0.09 AU, i.e., orbital periods between 1 and 10 days). About twenty Pegasi planets have been detected so far in our close neighborhood ($<$ 100 pc) by means of radial velocity surveys, which allows to characterize most of the orbital parameters of the companion planet and to estimate its mass through the product $M \cdot \sin i$. In one particular case (HD209458), the photometric observation of planetary transits in front of its parent star has allowed to access unambiguously to its mass (0.69 M_{Jup}) and radius (1.43 R_{Jup}). However, in order to infer the physical nature of the Pegasides and to test atmospheric models, spectroscopy of its own radiation is mandatory.

There is a particular interest in studying the physics of Pegasi planets because they have no equivalent in the Solar system and because none of the planet formation theory had predicted their existence. These hot, highly irradiated objects, showing synchronously locked rotation with their revolution period, are supposed to have formed far and then to have migrated towards the central star. Most models predict them to be gaseous giants, but they usually diverge on many important aspects of atmospheric modelling, such as the presence of aerosols and dust, the constitution of clouds, the thermalization between the irradiated and night hemispheres or the presence of high speed zonal winds. Figure 1 shows two examples of synthetic spectra for hot Jupiters, predicting very different spectral features. A spectral analysis of these objects would bring a considerable observational input to constraint these models.

Infrared spectroscopy in the $1.5 - 6$ μm region is particularly interesting for Pegasides because the contrast is lower than in the visible (typically raging between 10^5 and 10^3 from 1.5 to 6 μm) and above all because of the presence of important molecular species such as CH_4, CO and especially H_2O, which is difficult to observe from the ground because of atmospheric absorption.

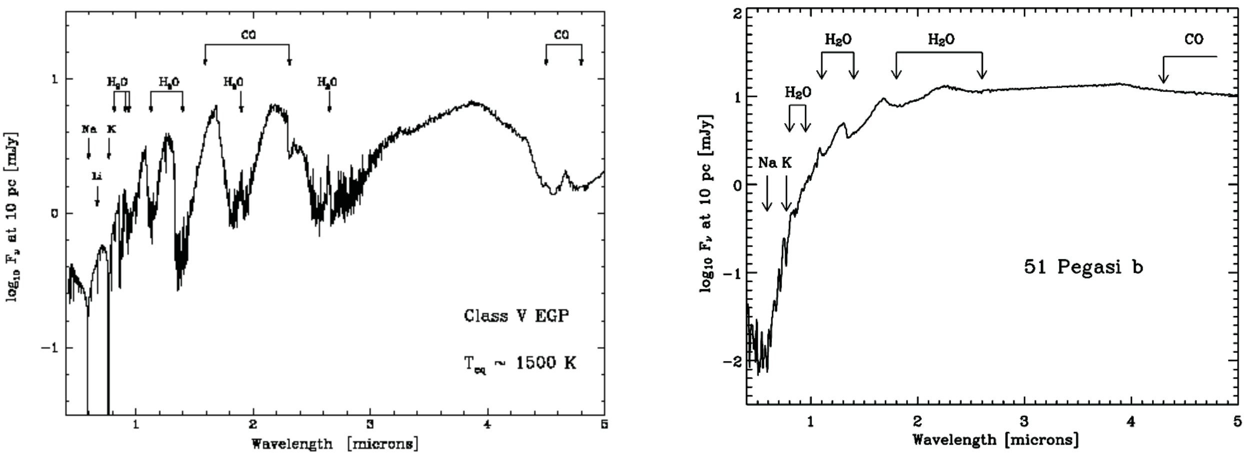

Figure 1: Examples of synthetic spectra for Pegasi planets with the same units and scale (left: from Sudarsky et al. 2003, right: from Barman et al. 2001).

2.2 Brown dwarfs

Even if the mass distribution of stellar and sub-stellar objects is continuous, stars differ from planets by their formation process. The limit between the two regimes is indicated by the very small number of bound objects with masses between 12 and 80 M_{Jup} (the brown dwarf desert). Provided that a large enough part of the infrared spectrum is accessible, the spectroscopic study of these scarce objects will allow to constraint the effective temperature, the radius, the composition and structure of their atmosphere. However, an estimation of the mass is mandatory to test the models for their internal structures and can only be accessed if the brown dwarf is bound in a multiple system: in that case, the mass can be estimated thanks to radial velocity measurements (the $\sin i$ ambiguity being lifted by interferometric or astrometric measurements). It is also expected that brown dwarfs will have been detected around young stars before Pegase is launched, so that evolution models will also be tested thanks to Pegase. The contrast between a Sun-like star and a brown dwarf typically ranges between 10^3 and 10^5 for a 1 Gyr-old system, which makes this kind of target well suited to Pegase.

2.3 Circumstellar disks

Protoplanetary disks belong to another group of objects for which high angular resolution combined with high dynamic range is needed. Their study directly relates to the planet formation processes. Pegase will bring precious information on such objects thanks to its high angular resolution and good spectral coverage in the near-infrared, in which both the reflected and thermally emitted radiations are accessible. The observation of the inner rim of the disk, corresponding to the sublimation radius of the dust grains ($0.1 - 0.4$ AU), is very important to understand the models accounting for the near-infrared of disks, which mostly comes from the hot inner dust. The possibility of a puffed-up inner rim will be investigated, and the comparison of the spectra at different baselines will bring information on the distribution of molecular species such as PAHs (through their 3.3 μm feature). Moreover, the interaction of the stellar magnetosphere with the inner dust, a currently unresolved problem in stellar formation, will also be studied by Pegase, as well as possible evidences of planet formation processes.

2.4 Additional goals

The expected performance of Pegase (see section 4) will allow a number of complementary objectives, such as:

- the study of the dust torus in active galactic nuclei,
- the extension of the programme on circumstellar disks to gas envelopes, stellar wind dynamics and debris disks, including the detection of exo-zodiacal light,
- the detection of coronal emission lines in active stars.

3 Instrumental concept

The baseline concept for the mission consist in a simple two-telescope interferometer formed of three formation flying satellites orbiting at the L2 Lagrangian point. Two Myriade micro-satellites are used as siderostats and one Proteus mini-satellite serves as beam-combiner (see Figure 2). The central Proteus bus holds the whole optical payload, consisting in two 40-cm telescopes, a fringe sensor operating in the visible for fine optical path control as well as visibility measurements, its associated small delay line, a star tracker for precise pointing, a chromatism compensator and a flux matching device, a beam-combiner for nulling interferometry, an infrared spectrometer with typical resolution of 60 and associated detection unit, the required metrology and sub-systems for configuration control, and finally an on-board CPU for data pre-processing (see Figure 3). The interferometric baseline ranges between 2×25 m and 2×250 m, or even 2×500 m if the phase A study shows that it is technically feasible.

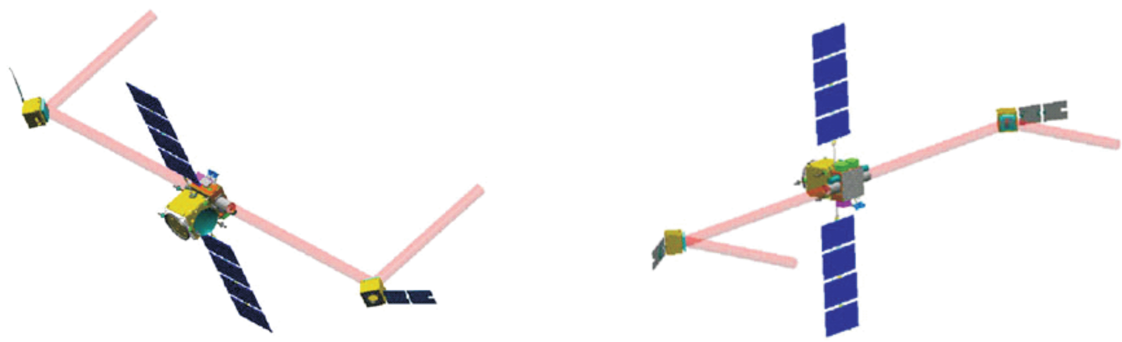

Figure 2: Flying configuration of the Pegase mission. The two siderostats bring both beams to the central platform where calibration, recombination and detection of the interferometric signal takes place.

The interferometric recombination comprises a simple visibility measurement mode by scanning the fringes with OPD dither (analogue to VINCI on VLTI) in addition to the nulling mode. The latter requires an achromatic phase shifter to be introduced in one of the two arms. A solution based on dispersive plates satisfies the requirements provided that the spectral range is divided into two channels. Modal filtering is used at beam recombination, using a fiber coupler or an integrated optics device. This type of recombination provides the required accuracy on wavefront quality, converting phase defects in the input beams into (less serious) intensity errors in the output beams. The working wavelength bandwidth must then be divided into two separate bands (1.5 to 3 μm and 3 to 6 μm) to take full advantage of modal filtering.

The detection unit features a HgCdTe focal plane array (e.g. from Rockwell or Sofradir), passively cooled down to 55 K, with a goal cut-off frequency of 6 μm (5 μm might be considered in order to relax the colling and thermal stability requirements). Thanks to the low spectral resolution, a simple prism spectrograph will be sufficient.

The fringe sensor will work in the $0.5 - 1.5$ μm regime, using a concept already proposed by ONERA in the context of the PRIMA fringe sensor (Cassaing et al. 2000): the four phase measurements of the so-called ABCD algorithm are formed simultaneously with an advanced beam-combining scheme that could well be implemented with an integrated optics component. This scheme also allows classical visibility measurements with the fringe sensor itself, so that additional science can be carried out in the visible. Precise diameter measurements with the visible beam-combiner should reveal very useful for the calibration of the nulling signal, where the stellar leakage depends on the angular size of the stellar disk. Advanced methods for hot Jupiter characterization in the visible are also considered, for instance using differential spectroscopy between the constructive and nulled outputs of the visible beam-combiner.

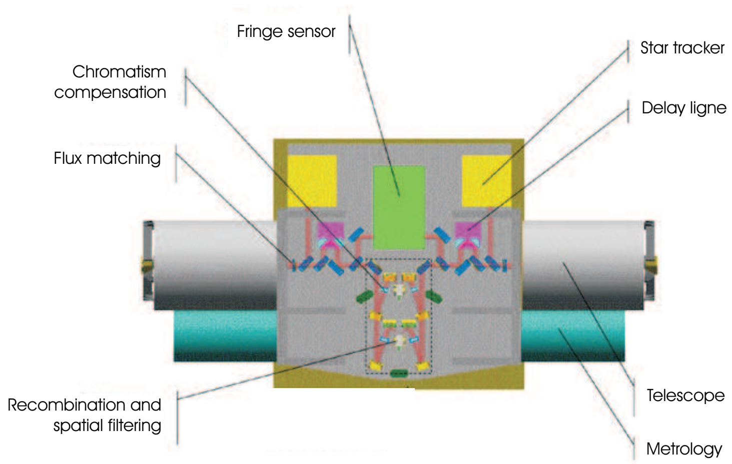

Figure 3: Payload located in the central satellite. The detection/spectroscopy unit is located on a second stage, which is fiber-linked to this stage.

During the 2-3 years of mission lifetime, about 50 targets are expected to be surveyed, with a duty cycle of about 50%: half of the time is spend in reconfiguring the array (baseline changes and rotations) and sending data towards the Earth with a high gain antenna.

4 Preliminary performance estimate

The performance of the nulling instrument on board the Pegase mission is estimated in Table 1 at $\lambda = 3$ μm and with a spectral resolution $R = 60$ for five possible targets. Four of them are hot Jupiters with various orbital parameters that have been detected by radial velocity surveys, while the fifth one is a smaller hot exoplanet, which, if gaseous, could be dubbed a hot Uranus[1]. In the first section of the table are defined the instrumental parameters. The baseline of the configuration has been tuned so as to place the planet on the first bright fringe of the transmission map of the nuller, assuming that the planet is observed at its maximum angular separation from the star. A decisive parameter of the instrument is its ability to maintain a

[1]We will assume that this planet is actually gaseous, so that its expected radius is about 0.4 R_{Jup}.

stable null. This ability is measured by the instrumental nulling: this is the nulling ratio one would get for an unresolved point-like source. Its value is determined by the contributions of optical path delay (OPD) errors and pointing errors which induce intensity mismatches in the single-mode fibres (polarization errors are assumed negligible). Another important parameter is the instrument temperature, which should be kept low enough to reduce the thermal background emission and stable enough to avoid so-called background fluctuation noise.

The stellar and expected planetary parameters are listed in the following sections of the table. The planetary temperature is computed from blackbody equilibrium. The geometric stellar nulling is the rejection factor on stellar light due only to the finite extent of the stellar disk, without instrumental errors. Due to the simplicity of the configuration (only two telescopes), this nulling ratio does not reach the initial star/planet contrast. Thus, the stellar flux in the nulling output will largely exceed the planetary signal, so that an additional calibration of the stellar leakage is required to actually detect the planet. This calibration can be achieved through a precise measurement of the stellar diameter by means of the visible interferometer on board Pegase. Another possibility is to use the rotation of the array to modulate the planetary signal in front of a constant stellar contribution. In practice, both methods will be used at the same time to improve the calibration accuracy.

The last source of photons in the nulled output is the thermal background emission from the local zodiacal cloud and the instrument itself. Its fluctuations are related to the possible temperature fluctuations of the optical elements. The local zodi emission is assumed to be stable in time.

The signal-to-noise ratio is divided into four contributions:

- The detection SNR, computed for an integration time of 1 hour, comprises the shot noise from all sources (including background) and the detector noise (mainly read-out noise: we assume a RON of 10 electrons rms and an individual integration time of 100 sec).

- The instrumental SNR is related to the fluctuations of the stellar leakage due to phase and intensity errors. The mean instrumental nulling, computed from the rms OPD and pointing error, is indeed equal to the expected rms fluctuation of the global nulling ratio. The expected stability of the stellar leakage is about 10^{-5} of the initial stellar flux, which should allow a good detectability of the planets listed here.

- The star calibration SNR is related to the calibration of the geometric stellar leakage. Its value mainly depends on the precision achieved on the stellar diameter measurement. A precision of 0.1% has been assumed in this study, which is realistic according to the current precision of ground-based interferometers such as VINCI on VLTI (fraction of a percent).

- The background fluctuation SNR mainly depends on the temperature of the instrument and on its fluctuations. The mean background will be subtracted by means of modulation methods. Note that this SNR is very high at 3 μm, but would become the limiting factor for detection at 6 μm because of the strong wavelength dependence of the blackbody emission.

The table shows that the hottest planets (T > 1000 K) are detected with a good signal-to-noise ratio ($\geq$ 10). About 10 such very hot targets have been detected so far by radial velocity measurements, and will be the primary targets for Pegase. The fourth planet in the table, with a temperature of 700 K, is barely detectable. This shows the approximate limit of the

Pegase detectivity. The fifth planet shows that Pegase should marginally detect hot Uranus-type planets, provided that they are hot enough. A significant number of such planets are expected to be detected in the coming years with high-precision radial velocity surveys.

5 Conclusions

In this paper, we have briefly presented a proposal for a space interferometer recombining the lights collected by two free-flying siderostat spacecrafts separated by baselines ranging between 25 and 500 m. Its main scientific goals are the spectroscopic study of hot giant extra-solar planets (Pegasides), brown dwarfs and circumstellar disks in the near-infrared domain (1.5 to 6 μm), with a possible extension towards the visible wavelengths. The main recombination mode consists in a nulling interferometer, particularly well suited to study high-dynamic targets. A simple visibility measurement mode will also be implemented. Preliminary performance estimates show that Pegase should be capable of characterizing Pegasi planets within one to a few hours of integration with a low spectral resolution (R=60). If selected by CNES, Pegase could be launched around 2012.

Acknowledgements

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	Tau Boo b	51 Peg b	HD209458 b	HD162020 b	55 CnC e
1. Instrument					
Diameter [m]	0.4	0.4	0.4	0.4	0.4
Baseline [m]	90	80	300	120	100
Wavelength [μm]	3.0	3.0	3.0	3.0	3.0
Spectral resolution	60	60	60	60	60
Field-of-view [mas]	700	700	700	700	700
Total instr. throughput	0.03	0.03	0.03	0.03	0.03
Instr. temperature [K]	100	100	100	100	100
RMS temp. fluctuation [K]	1.0	1.0	1.0	1.0	1.0
RMS OPD error [nm]	3.0	3.0	3.0	3.0	3.0
RMS jitter [mas]	40	40	40	40	40
Instrumental nulling	95000	95000	95000	95000	95000
2. Star					
Distance [pc]	15.6	14.7	47	31.3	13
Angular radius [mas]	0.36	0.41	0.11	0.12	0.31
T_{eff} [K]	6276	5770	6030	4890	5458
Flux [Jy]	12.5	14.2	1.06	0.32	7.62
Geometric stellar nulling	145	143	145	765	157
Output flux [ph-el/s]	165	188	13.9	2.29	92.1
3. Planet					
Mean orbit [AU]	0.050	0.051	0.045	0.072	0.038
Mean angular sep. [mas]	3.21	3.48	0.96	2.30	2.92
Expected radius [R_{Jup}]	1.1	1.1	1.1	1.1	0.4
Expected albedo	0.35	0.35	0.35	0.35	0.35
Equilibrium temp. [K]	1343	1259	1291	705	1136
Thermal + refl. flux [Jy]	1.1×10^{-4}	1.0×10^{-4}	1.1×10^{-5}	1.2×10^{-6}	1.1×10^{-5}
Initial star/planet contrast	3300	4150	2900	21500	19850
Output flux [ph-el/s]	7.14	6.32	0.68	0.08	0.72
4. Background					
Local zodi [Jy/sr]	1.37×10^5	1.37×10^5	1.37×10^5	1.37×10^5	1.37×10^5
Instr. brightness [Jy/sr]	2.18×10^{-3}	2.18×10^{-3}	2.18×10^{-3}	2.18×10^{-3}	2.18×10^{-3}
Bckg fluctuations [Jy/sr]	2.17×10^{-3}	2.17×10^{-3}	2.17×10^{-3}	2.17×10^{-3}	2.17×10^{-3}
Output flux [ph-el/s]	9.3×10^{-3}	9.3×10^{-3}	9.3×10^{-3}	9.3×10^{-3}	9.3×10^{-3}
5. Signal-to-noise ratios					
Detection SNR	32.6	27.1	10.4	2.6	4.5
Instrumental SNR	28.5	22.2	32.2	4.3	4.7
Star calibration SNR	43.4	33.6	49.3	34.3	7.8
Bckg fluctuation SNR	1.5×10^9	1.3×10^9	1.4×10^8	1.6×10^7	1.5×10^8
Total SNR	19.2	15.3	9.7	2.2	3.0

Table 1: Expected performance for the detection of Pegasides.