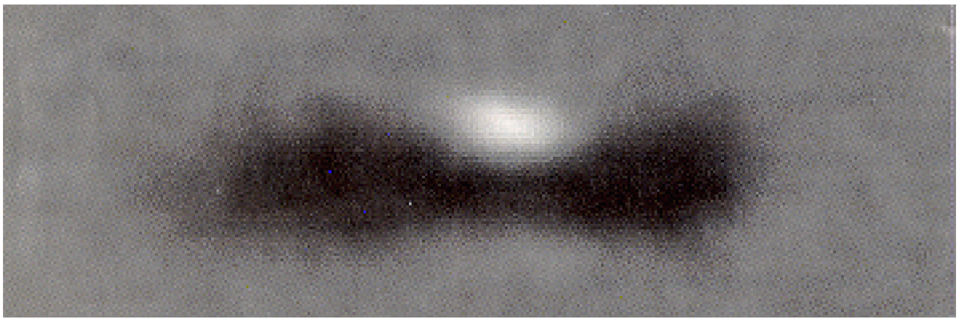
Characterisation of zodiacal environment of stellar targets for future missions dedicated to the direct detection of extrasolar planets



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Abstract : The level of brightness and the structure of exozodiacal dust clouds is identified for a long time as a limiting factor for the direct detection of extrasolar planets, their imaging and the characterisation of their atmosphere. In this (white) paper, we point out the sensitivity required to detect and analyse this zodiacal emission and discuss several concepts, particularly space-borne ones. We thus show that a small nulling interferometer mission in space with moderate aperture (several tens of centimetres) is particularly suited for observations of zodiacal disks at a level of 1 solar zodi.
We consider the study of exozodi as a step of strong relevance on the pathway to earth like planet characterisation. The study of exozodi is important for preparing future mission like Darwin : source list, constraints on the size of the mission and on observing procedures. In addition the measurements of brightness zodi levels and geometries will provide signatures on the presence and amount of minor bodies (asteroids and comets).

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Science case

Among the parameters requested to study the direct detectability of extrasolar planets, the contribution of exozodiacal light (emission of the interplanetary dust as in our own Solar System) is certainly one of the most uncertain one.

Whatever the instrumental techniques and the associated spectral range could be, coronagraphy in the visible spectral range, nulling interferometry in the thermal infrared spectral range, exozodiacal light emission has been identified as a critical issue at a level equal to or higher than 10-20 solar zodis (Beichman et al., 1999, Fridlund et al., 2000). At this level, namely, and even with the use of instrumental tricks (internal modulation, rotation of the instrument…) the shot noise associated to the exozodiacal emission becomes one of the major contributions to the overall noise (Mennesson et al., 2005, Beichman et al., 2006).

In our Solar System, the global emission of zodiacal light at λ = 10 μm is about 300 times larger than the Earth'one. Even if physical processes (pointing Robertson effect) should tend to reduce the amount of dust in the interplanetary space, the cometary evaporation and asteroids collision phenomena generate small particles. The balance between dust evaporation and dust particles production merits to be better understood for different stellar environments.
Other debris disks have been observed around several stars (Vega, β Pictoris, Polaris, Fomalhaut…), either by infrared excess detection or (and) by direct imaging, but, because of sensitivity limitations, only in the case of bright objects with levels of several hundreds of solar zodis. 82 stars (mostly F, G and K main-sequence stars) have recently been observed using the MIPS instrument on Spitzer (Beichman et al., 2006). Observation of infrared excess at λ= 24 μm and λ = 70 μm brought new clues for identification of some new debris disks. However, the moderate detectability of Spitzer misses still a factor 50-100 to reach the detectability requested to observe 10-20 solar zodi emissions.

More than the global value of the zodiacal flux, it is also the spatial distribution of the dust through its corresponding brightness map that should clearly be analysed. The inhomogeneous dust distribution in the debris disk (at Lagrangian points for instance) can mimic the signal from a planetary object (Fig. 1).

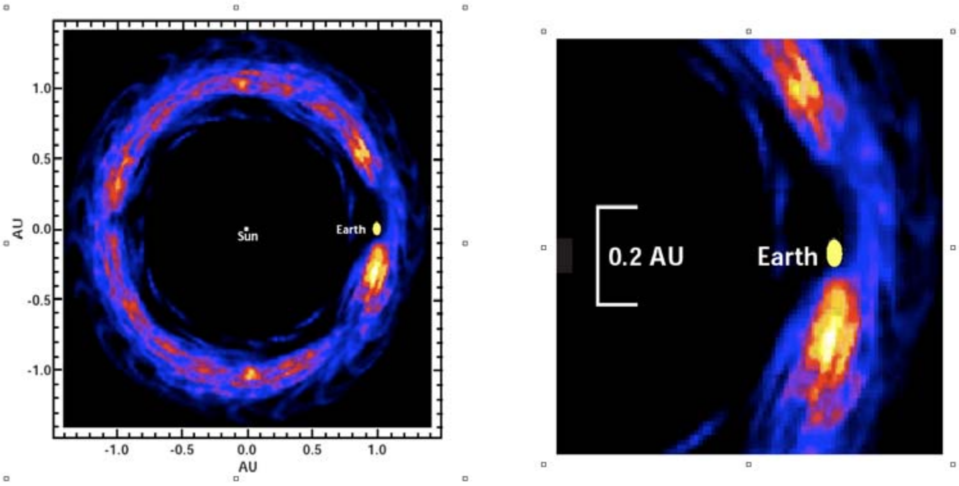

Fig. 1 : (Left) Structure of the Solar System zodiacal disk. (Right) Detailed structure of the disk around the Earth, showing clearly the existence of local over-densities of dust that can mimic the presence of a planetary object (from Beichman et al., 1999).

The modelling of disk properties will be of importance. For instance the ZODIPIC model and software developed by M. Kuchner allows generating multi-chromatic maps of dust disks. One of the key-issue of such models is the capability to simulate the brightness computation at several wavelengths when observation is performed in a limited spectral domain. Such software allows adding over densities, but very few observational constraints do exist for the moment.
In addition to the foreseen necessity to produce direct dust disk mapping through observations of stellar environments, the realistic ranges within which the model parameters could vary have also to be determined through observations and empirical modelling. Extrapolations of disk brightness properties in the wavelength domains within which the exo-earths will be characterized will then become possible.

Technical approaches

Several approaches have been proposed to assess the question of exozodiacal level either from the ground of from space. The major difference between ground-based and space-borne concepts is their sensitivity.

Ground based concepts:

Several instruments have been studied during the last ten years. Among them, 3 appears to be particularly suited for exozodis science:

The Large Binocular Telescope : Installed at the top of Mont Graham, the LBT is composed of two 8.4m telescopes separated by 14.4 m. With very few optical components, and the possibility to be used as a nulling interferometer, the LBT is perfectly suited for the detection and characterization of exozodi in the thermal IR, at a level reaching potentially 3 solar zodis. Unfortunately, this facility should not be easily open to the European community.

Denis : ce n est pas me semble t il une raison suffisante pour justifier une mission spatiale. Si le LBT peut vraiment faire 3 zodis, tout le monde beneficiera de ces resultats pour la preparation d une mission comme Darwin. Je ne vois pas comment bien tourner la fin de ce paragraphe. Il faudrait lire (ce que je n ai pas le temps de faire) ce qui est ecrit dans les science cases du LBT. Si tu as moyen d y consacrer un peu de temps avant l envoi de notre lettre…

The instrument GENIE (Ground-based European Nulling Interfermetry Experiment) has been studied by ESA, ESO and industrial contractors in the beginning of the decade (Wallner et al. 2006). Its goals were multiple, and particularly, the study of exo-zodiacal environments. However, the complexity of existing facility (VLTI and coudé train) to which GENIE should be connected (including existing fringe sensor units, delay lines, AO systems, …), the quality of the astronomical site and the fact that some pieces of the VLTI were not optimized for nulling interferometry techniques led to a concept of expansive, risky instrument with a level of performance limited with respect to the science case (sensitivity at best equal to several tens of solar zodi).

The ALADDIN concept is born at the end of GENIE study (Coudé du Foresto et al. 2006). Starting from the conclusion that the Paranal facility was not optimized for the observation of stellar environments by nulling interferometry, ALADDIN was developed as a brand new facility, with dedicated and optimized telescopes and optical train, in an astronomical site dedicated to the characterization of stellar environment (Dome C in Antartica). The concept of ALADDIN should be detailed in a separated white paper.

Space-borne observatories.

The main drawbacks of ground-based concepts are linked to :

- Ambient temperatures, generating (variable) sky background level as well as telescope and optical background contribution in the mid-infrared domain,
- Atmosphere turbulence which is a source of un-stability affecting nulling ultimate performances and calibration potential.

Space-borne observation appears to be a valuable alternative to avoid atmospheric disturbance. We already mentioned that Spitzer was used to detect infrared excess but because of its lack of sensitivity, it is not able to study dust clouds less bright than several hundreds of solar zodi.
Observation of stellar environments with JWST will be possible thanks to the MIRI (Mid InfraRed Instrument) a camera that will be equipped with a coronagraph, reducing the level of stellar emission, allowing the observation of stellar neighbourhood.

According to the point of view that ground based facility have a limited performance because of the atmosphere, and considering that for observations of dust disks in the mid-infrared spectral range requires angular resolutions corresponding to the astronomical unit for nearby stars, two space-borne concepts were studied : one at CNES (France) called PEGASE and the other one at NASA (USA) called Fourier Kelvin Space Interferometer (FKSI).

PEGASE

PEGASE (Fig. 2) is a two free flyer telescope nulling interferometer. In its first version (linear version) baselines could vary from 50 to 500 m to allow various science cases, including the spectroscopy in the near infrared (1.5 – 6 μm) of low mass objects such as low mass stars, brown dwarfs and hot jupiters, and the study of zodiacal environment at shortest baselines. The mission concept was extensively described in an answer to ESA's first call for proposals for the Cosmic Vision program (Ollivier et al., 2007). In the context of exozodi characterisation, a non linear configuration is under study to reduce the minimum baseline to 5 to 10 m. In this configuration, the beam combiner is at the top edge of an isoceles triangle, the two siderostats are at the other edges. The drawback of such configuration is the way s and p polarisations are treated, a priori more complex than in the linear configuration case.

Figure 2 : artist's view of PEGASE (Courtesy Alcatel Alenia Space)

FKSI

The FKSI implementation is a two-telescope passively cooled nulling interferometer operating between 3 and 8 μm (Danchi et al. 2003 and 2004). The FKSI observatory will operate at the second Sun-Earth Lagrange point (L2) in a large amplitude Lissajious (or halo) orbit. While we have explored a range of aperture sizes for FKSI, our baseline design employs 0.5 m apertures. The telescopes employ two flat mirrors (siderostats) mounted 12.5 apart on composite support booms (see Fig. 3), minimizing alignment requirements for the beams that enter the instrument package. The booms support sunshades that allow passive cooling of the structure to 60K, reducing thermal noise in the telescope system to a level that is negligible compared to that from the local zodiacal cloud (zodiacal background limited performance) over most of the instrument passband.

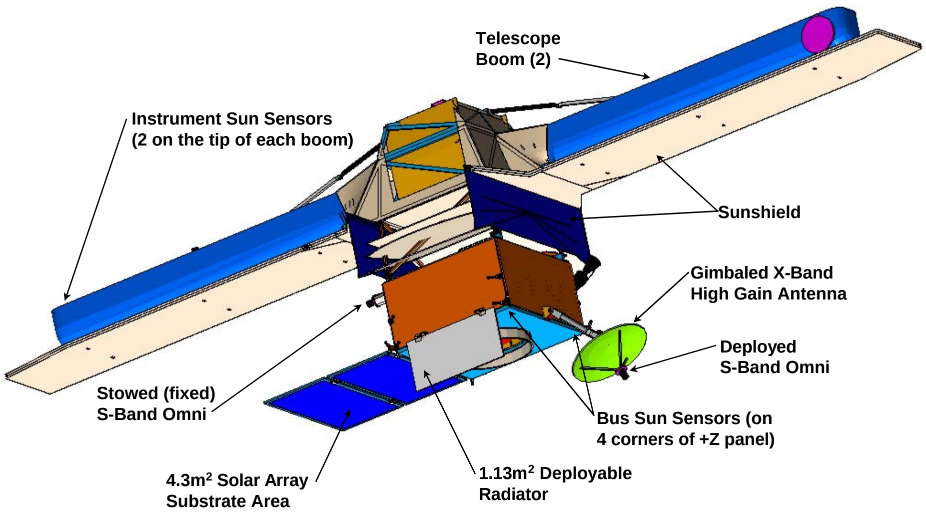

Figure 3 : The FKSI mechanical design.

Comparison between both ground-based and space-borne concepts

The comparison between Antartica and other ground based sites in the context of exozodi characterisation by a nulling instrument has been done by Absil et al (2007). They conclude to the superiority of Antartica over other sites in terms of sensitivity of the instrument (mainly because the atmospheric stability of the site).

The comparison between Antartica, other ground-based sites and space borne concepts has been performed by Defrère et al (2008). The results are summarised in Fig. 4 and Table 1.

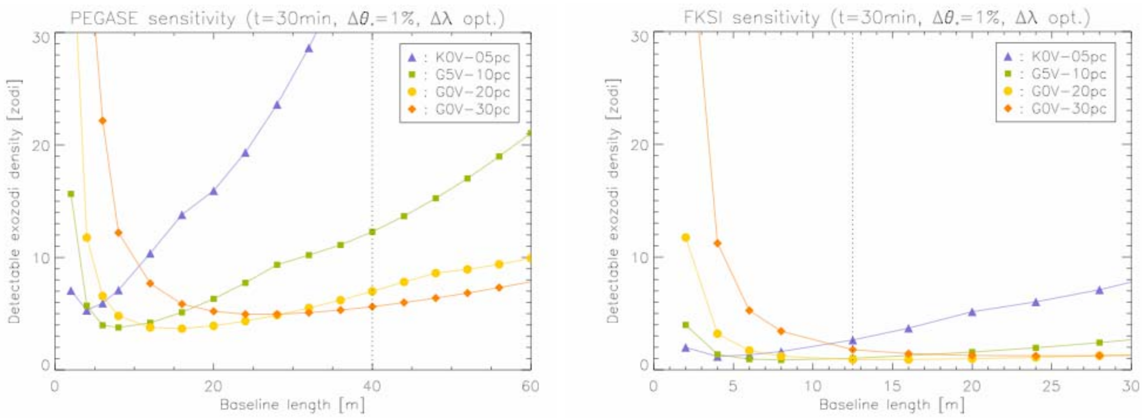

Figure 4 : comparison between PEGASE (linear configuration) and FKSI performance. The main performance differences can be explained by the minimal achievable baselines (FKSI allows smaller baselines because of the single spacecraft configuration) and the slightly different spectral range (from Defrère et al. 2008).

Star	0.25%	0.5%	1%	1.5%	Instrument
K0V - 05pc	110	230	450	680	GENIE - UT
	20	33	55	79	ALADDIN
	12	21	40	60	PEGASE
	0.9	1.4	2.6	3.9	FKSI
G5V - 10pc	30	59	120	180	GENIE - UT
	15	24	37	51	ALADDIN
	4.7	8.3	12	17	PEGASE
	0.5	0.7	1.0	1.4	FKSI
G0V - 20pc	21	29	50	73	GENIE - UT
	19	25	37	48	ALADDIN
	2.8	4.2	7.0	9.5	PEGASE
	0.7	0.8	0.9	1.1	FKSI
G0V - 30pc	36	46	59	71	GENIE - UT
	62	63	67	72	ALADDIN
	3.1	3.9	5.5	7.3	PEGASE
	1.7	1.7	1.8	1.9	FKSI

Table 1 : Performance comparison between ground-based concepts and space-bornes ones expressed in detectable exozodiacal disc densities as compared to the solar zodiacal disk for different uncertainties in the stellar angular diameter measurement and an integration time of 30 min (from Defrère et al., 2008)

The conclusions of such study are multiple:

- VLTI environment is not suitable at all for exozodi studies
- Antartica can be a good trade-off if a knowledge of exozodi brightness at a level of a few tens solar zodis is sufficient.
- Space borne concepts are required if a knowledge of exozodi brightness at a level of a few solar zodi is required

J ai enlevé la derniere phrase qui est redondante avec l ensemble de la lettre et n apporte rien je pense ici.

Concept summary and technical maturity

PEGASE and FKSI concepts have been described in many papers (Le Duigou et al. 2006, Danchi et al. 2003 and 2004). Both concepts are nulling interferometer (Bracewell 1978): the stellar light is strongly reduced by destructive interference allowing observation of off-axis targets (stellar environment).
Table 2 summarizes the main characteristics of PEGASE.
An evaluation of the nulling and Optical Path Difference error budgets for FKSI is given.

	PEGASE
N of spacecraft	3 : (2 siderost. 1 Beam comb) free flying configuration
N. of apertures (diam.)	2 (0.4 m)
Spectral range	2.5 – 6 μm
Spectral resolution	50
Baselines	20-500 m (continuously adjustable) in the linear configuration 5-200 m (continuously adjustable) in the triangle

	configuration (under study)
Max angular resolution	1 mas at 2.5 μm
Spacecraft pointing	A few arsec
Fine pointing	20 mas
Optical path difference control	2.5 nm rms
Nulling ratio	10^{-4}
Nulling stability	10^{-5}
Achromatic Phase Shifter specifications	5.10^{-3} rad
Fine propulsion	Improved cold gas
Optics temperature	100 K
Detector temperature	55 K
Orbit	L2

Table 2 : main characteristics of PEGASE concept.

Concerning FKSI for instance, the nulling instrument is based on a modified Mach-Zehnder beamsplitter design that maximizes the symmetry of the two beams, helping to ensure a deep null. Other elements in the system include shutters for alignment and calibration purposes, an assembly for amplitude control of the fringe null, and optical fibers for wavefront cleanup. The fibers help achieve the desired null depth with reduced tolerances on the preceding optical components (in order to reduce manufacturing costs). The dark and bright outputs are sent to their respective Focal Plane Arrays (FPAs) that are long wavelength HgCdTe arrays from Teledyne (previously Rockwell) operating at 35K. The FPAs for the fringe and angle trackers are operated at 77K and are based on the HgCdTe NICMOS arrays. Cryogenic delay lines are used to equalize the pathlengths between the two sides of the interferometer.

When the instrument is in operation, it rotates slowly around the line of site to the object. In doing so, a sinusoidal signal is generated at the output of the nuller instrument, which is non-zero if there is a planet or material within the transmission pattern of the nuller.

The concept has undergone a thorough integrated analysis and modelling study of the structure and optics to validate the design and ensure it meets requirements (Hyde et al. 2004). The null depth requirement drives the instrument performance. Contributions to the performance error budget for the required 10^{-4} null are shown in Fig. 5 and a sample nulling error budget is shown in Fig. 7. The allocation of the 15 nm optical pathlength difference (OPD) term is shown in Fig. 8.

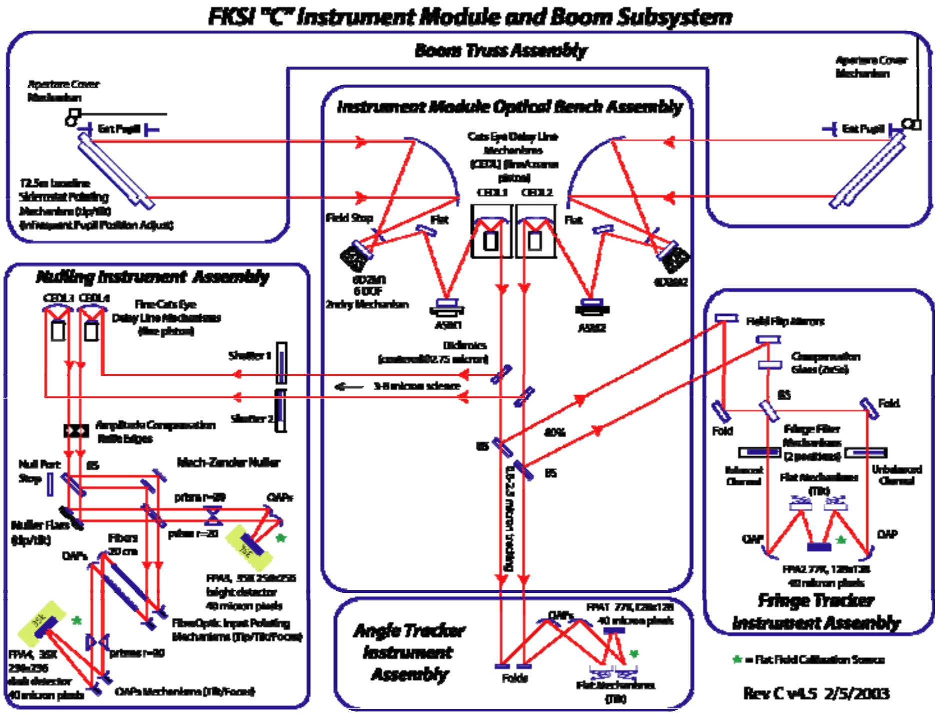

Figure 5 : Schematic design of the boom and instrument module subsystem for FKSI. The various subassemblies are as noted in the figure.

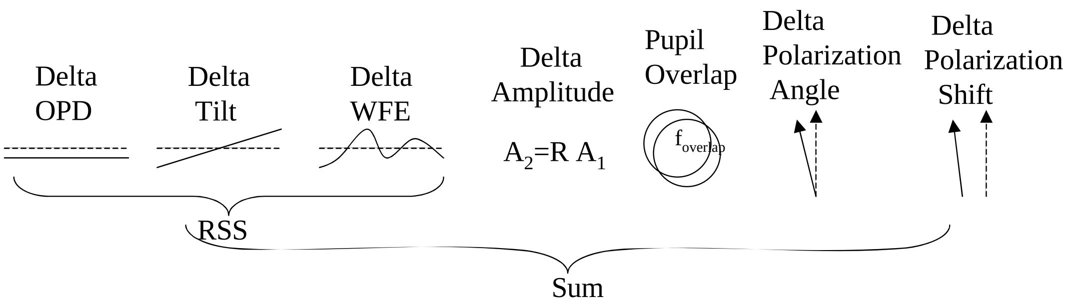

Figure 6 : Major contributors to nulling error budget

Term	Null loss formula	Tolerance on	Tolerance		Null loss
OPD, rms	$(2\pi z/\lambda)^2/4$	z	15	nm	0.000073
Tilt, rms	$(\pi D\alpha/\lambda)^2/8$	$D\alpha$	34	nm	0.000012
WFE, rms	$(2\pi\sigma/\lambda)^2/4$	σ	6	nm	0.000012
Amplitude match	$1-2/(R^{1/2}+R^{-1/2})$	$1-R=1-A_1/A_2$	1.2	%	0.000004
Pupil area overlap	$1-f_{overlap}$	$1-f_{overlap}$	NA	%	NA
Polarization match	$\theta^2/4$	θ	0.36	deg	0.000010
Polarization shift match	$(\theta/2)^2/4$	θ	0.72	deg	0.000010
					0.000099

Figure 7 : Nulling Error Budget

Source	OPD, nm
FT noise	5.0
ODL noise	5.0
ACS induced	7.0
Boom induced	1.1
RWA induced	6.0
Margin	9.4
RSS Total	**15.0**

Figure 8 : OPD Budget

Both concepts are based on studies performed at JPL and in Europe thanks to space agencies fundings (including ESA, in the context of DARWIN ITTs). According to the level of performance required by the beam combiner, laboratory test bench is achieved for PEGASE concept (Ollivier et al. 2007). PEGASE 0 level study performed at CNES exhibited no show-stopper. In addition, a specific program of R&T is under way in France thanks to a CNES initiative, concerning PEGASE. The PERSEE test bench (Pegase Experiment for Research and Stabilization of Extreme Extinction) should allow to validate the concept of nulling interfermetry in the framework of formation flying. The bench will thus gather both classical nulling interferometry beam combining unit and perturbations generators to simulate formation flying constellation behaviour. Such a facility will allow the validation of servo control and correction algorithms, so as associated optical components.

Denis, J enleverai toute cette partie : In addition, and even if no interferometric mission ever flew and formation flying is at its very beginning, the experience gathered during the PRISMA, SIMBOL-X, PROBA-3 studies can be valued for the definition of a first nulling interferometry mission. In addition, the reduced level of performance PEGASE or FKSI require, compared to DARWIN’s one (initial proposal), would allow a real conditions validation of this technique while first level science is performed.

Proposal to ESA EPR-AT

We would like to point out to EPR-AT that the issue of stellar environments (exozodiacal brightness level, disk geometry, dust characteristics) appears to us of strong relevance in the pathway towards the direct characterisation of extrasolar planets and particularly telluric ones. A good knowledge of the circumstellar environments around nearby stars will permit to better specify the future instrumental design and observing procedures for Earth like characterisation.
We suggest ESA EPR-AT to consider dedicated missions and studies for progressing on this research field which has important implications. We also propose several instrumental concepts.

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