CAN GENIE CHARACTERIZE DEBRIS DISKS AROUND NEARBY STARS?

O. Absil[1], L. Kaltenegger[2], C. Eiroa[3], R. den Hartog[2], P. Gondoin[2], R. Wilhelm[4], and M. Fridlund[2]

[1]Institut d'Astrophysique et de Géophysique, Université de Liège, Belgique (e-mail: absil@astro.ulg.ac.be)
[2]Science Payloads and Advanced Concepts Office, ESA/ESTEC, Noordwijk, The Netherlands
[3]Dpto. de Física Teórica, Facultad de Ciencias, Universidad Autónoma de Madrid, Cantoblanco, Spain
[4]European Southern Observatory, Garching bei München, Germany

ABSTRACT

The Ground-based European Nulling Interferometer Experiment will combine the light collected by two or more VLT telescopes and make them interfere in a destructive way, thereby revealing the close neighborhood of nearby stars. Operating at mid-infrared wavelengths, GENIE will be particularly sensible to warm circumstellar dust. This paper presents simulated observations of the debris disk around the nearby A2V star zeta Leporis obtained with the GENIE simulation software. Parameters such as inclination, density power-law exponent and inner radius can be retrieved with a relative precision of 1% or better using only six observations of 15 minutes. In the context of the DARWIN/TPF mission, warm circumstellar dust could be a serious limitation to the detection of Earth-like exoplanets. This paper shows that GENIE will detect disks as faint as 23 times our local zodiacal cloud around Sun-like stars at 10 pc, and will thus allow to discard unsuitable targets for DARWIN/TPF.

Key words: Debris disks; Vega-type stars: zeta Leporis; infrared; nulling interferometry; GENIE.

1. INTRODUCTION

The GENIE instrument, a common project of the European Space Agency and of the European Southern Observatory, should be installed in the interferometric laboratory of the Very Large Telescope (Cerro Paranal, Chile) in 2007. The first goals of this instrument are to validate the concept of nulling interferometry for the DARWIN/TPF mission and to perform nulling tests on single stars, with the deepest and most stable starlight rejection rate (Gondoin et al., 2003).

Besides its technological aspects, GENIE aims at surveying nearby main-sequence stars for the presence of warm dust around them, especially in their habitable zone, to prepare the science programme of the DARWIN/TPF mission by discarding unsuitable targets (i.e., those surrounded by a too large amount of dust). This survey should also bring brand new information on the inner dust component of debris disks, which is very difficult to investigate without high angular resolution.

The main-sequence stars currently known to harbor a large quantity of dust are mainly early-type stars. They were called Vega-type stars after the first discovery of an excess infrared flux around Vega by the satellite IRAS (Aumann et al., 1984). The geometrically and optically thin dust disks surrounding these stars are supposed to be continuously replenished by evaporating comets and colliding asteroids, the remnants of the proto-planetary disks being removed within a few Myr by processes such as radiation pressure, Pointing-Robertson drag or sublimation.

In this paper, we have simulated observations of a typical Vega-type star, zeta Leporis (ζ Lep hereafter), by means of the GENIEsim simulation software (Absil et al., 2003). Warm dust has already been detected around this particular star, and a model for the disk morphology is available (Fajardo-Acosta et al., 1998). Our simulated observations show that GENIE could provide an unprecedented accuracy in the modeling of the disk morphology, and thus on the physics of such disks.

2. MODELING DUST DISKS AROUND MAIN-SEQUENCE STARS

Debris disks around main sequence stars are generally modeled as flat optically thin disks, bounded by an inner radius $r_{\rm in}$ and an outer radius $r_{\rm out}$. The morphology of the dust cloud is described by the following density and temperature power-laws:

$$\rho(r_c) \quad = \quad \rho_0 \left(\frac{r_c}{r_{\rm in}}\right)^{-\alpha} \qquad (1)$$

$$T(r_c) \quad = \quad T_{\rm in} \left(\frac{r_c}{r_{\rm in}} \right)^{-\delta} \qquad (2)$$

In these two expressions, we have neglected the vertical dependence of the dust properties, and r_c represents the distance to the star projected on the ecliptic plane of the system. This is an acceptable approximation assuming that the disk is geometrically thin.

Table 1 lists the parameters with which Fajardo-Acosta et al. (1998) have modeled the hottest part of the dust disk around ζ Lep. This model reproduces 90% of the observed flux at 10.3 μm. Of particular interest is the fractional dust luminosity ($L_{\rm dust}/L_*$), the ratio of integrated excess flux emitted from the dust to integrated flux emitted from the star alone. According to Backman and Gillett (1987), this ratio is equivalent to the mean optical depth of circumstellar dust grains, and is thus an indicator of the quantity of dust around the star.

Table 1. Star and disk parameters for the Vega-type star ζ Lep.

Stellar parameters		Disk parameters	
Distance [pc]	24	$r_{\rm in}$ [AU]	0.5
V mag.	3.55	$r_{\rm out}$ [AU]	7
Type	A2V	$T_{\rm in}$ [K]	960
R_* [$R_\odot$]	2.3	$T_{\rm out}$ [K]	250
$T_{\rm eff}$ [K]	9250	α	0.6
L_* [$L_\odot$]	35	δ	0.5
		$L_{\rm dust}/L_*$	1.7e-4

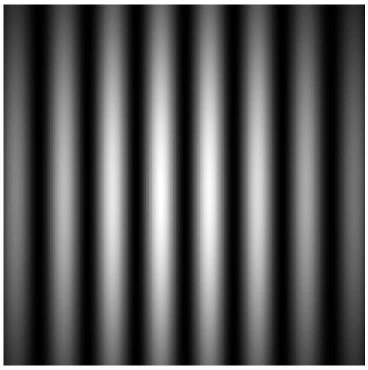

Figure 1. Transmission map of a 46 m Bracewell interferometer formed of two UT's. The spacing between two bright fringes is respectively of 17 mas and 47 mas at 3.8 μm and 10.5 μm, which correspond respectively to 0.4 AU and 1.1 AU for ζ Lep.

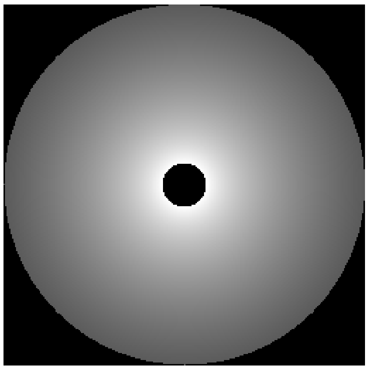

Figure 2. Simulated image of the dust disk around ζ Lep seen face-on in the N band (logarithmic scale), in the interferometric field-of-view of a UT.

3. INSTRUMENTAL CONFIGURATION

It is not currently known if GENIE will operate in the infrared L' band (3.5–4.1 μm) or N band (8–13 μm). The final choice of the operation wave band mainly depends on technological aspects and on calibration issues for background and stellar leakage (Gondoin et al., 2003). We will thus simulate observations both in the L' and N bands. Due to the huge thermal background in the mid-infrared N band, only the 8 m Unit Telescopes (UT's) will be used in this band, while in the L' band the less sensitive 1.8 m Auxiliary Telescopes (AT's) are affordable.

The simulations are done for a two-telescope Bracewell configuration. We have used the preliminary design of the GENIE instrument discussed in Absil et al. (2003), and currently implemented in the GENIEsim science simulator. This design includes control sub-systems for optical path delay, longitudinal dispersion and intensity mismatch between the two beams. The transmission map of the instrument is shown in Figure 1. The radius of the interferometric field-of-view is respectively of 277 milliarcsec (mas hereafter) for an AT in the L' band, and of 172 mas for a UT in the N band, which correspond respectively to 6.7 and 4.1 AU at the distance of ζ Lep. Thus the inner part of the cloud that we have modeled fills the field-of-view in both cases.

4. INFLUENCE OF THE DISK PARAMETERS ON THE NULLING RATIO

Using the above model and the DISKPIC package (Absil et al., 2003), we have generated the image of the ζ Lep dust cloud within the interferometric field-of-view of AT's and UT's (see Figure 2 for a UT in the N band). A constant thickness of 0.1 AU was assumed for the dust cloud. The flux of the disk within the field-of-view is respectively of 0.18 Jy and 0.46 Jy in the L' and N bands, in agreement with the excess observed by Fajardo-Acosta et al. (1998): $<$ 0.9 Jy in the L' band, 0.43 Jy in the N band.

In the following paragraphs, we have generated images of the dust cloud with different parameters, to assess the influence of each disk parameter on the theoretical nulling ratio. The *nulling ratio* is defined as the ratio of the total flux collected in destructive mode to the total flux in constructive mode (i.e., without the π phase shift between the arms of the interferometer). The nulling ratio is called "theoretical" because noise is not taken into account.

The simulated observations are performed when the star crosses the local meridian, at a zenithal distance of 9°48'. Such a small zenithal distance ensures that the projected baseline on the plane of the sky has approximately the same length as the actual baseline, e.g. 46.65 m for the UT2-UT3 pair. These simulations are only performed in the N band—the L' band would give the same qualitative results. The only difference between the two bands is that the *physical leakage*, i.e., the theoretical leakage from the stellar light, is negligible in the N band while not in the L' band due to higher angular resolution (especially for long baselines). If the stellar diameter is known with a high enough accuracy, the physical leakage can be removed from the nulling ratio to reveal the contribution of the disk itself. Otherwise, the stellar diameter needs to be fitted together with the disk parameters.

4.1. Influence of inclination

We have generated images of the dust cloud with different inclinations, ranging from 0° (face-on) to 90° (edge-on), and we have computed the theoretical nulling ratio for these configurations. Figure 3 shows the evolution of the nulling ratio as a function of the baseline orientation for different inclinations of the disk. The baseline angle is counted clockwise with respect to the N-S direction. A position angle of 0° was assumed for the dust cloud (i.e., major axis along the N-S direction). For low inclinations, the nulling ratio is not affected by the baseline orientation, because the disk image has nearly circular symmetry. For high inclinations, the flux in destructive mode drops dramatically when the dark fringe and the major axis of the disk are superposed (baseline angle of 90°).

4.2. Influence of the morphology

In Figures 4 and 5, we have used different values of the density power-law exponent α and of the inner radius r_{in} to generate the cloud images. The nulling ratio has been computed for different baseline lengths ranging from 40 m to 140 m. The influence of the inner radius on the nulling ratio is remarkable: the maxima of the curves in Figure 4 correspond to the baselines at which a bright fringe is superposed on the inner component of the dust cloud (brightest part of the cloud). On the other hand, the density power-law exponent has a smaller influence on the nulling ratio: the position of the maximum does not change any more, and the behaviour of the nulling ratio with increasing baselines is similar for all values of α. Retrieving this parameter from nulling measurements will not be easy.

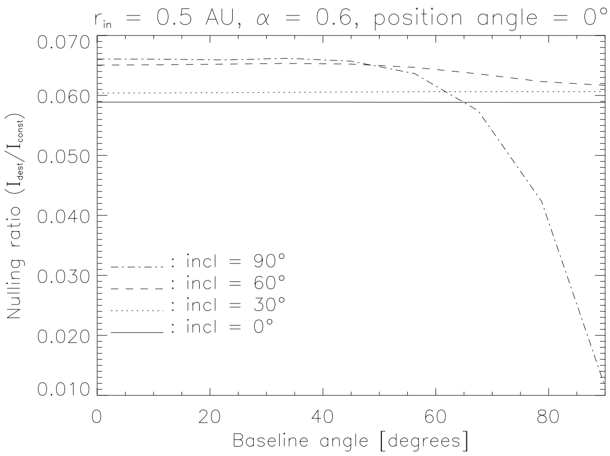

Figure 3. The evolution of the nulling ratio for different baseline orientations is remarkable for high inclinations: when seen edge-on, the disk is strongly cancelled by a dark fringe for a baseline angle of 90°.

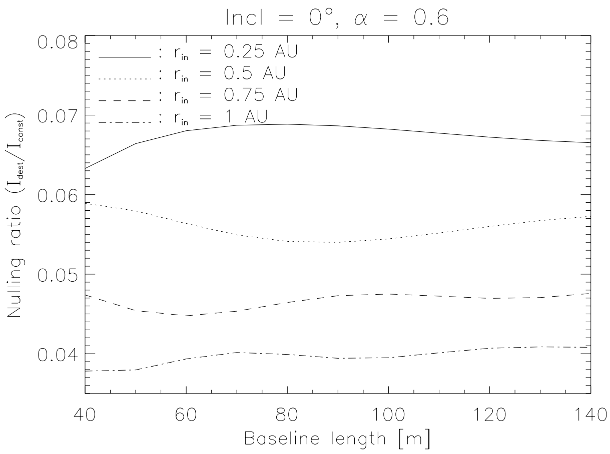

Figure 4. The influence of the dust inner radius is remarkable: the nulling ratio is maximum when a bright fringe transmits the large flux produced by the hot dust located at the inner cut-off.

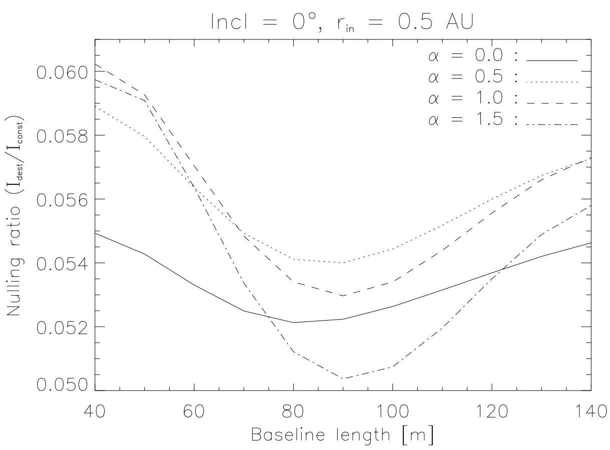

Figure 5. The behaviour of the nulling ratio for different density power-laws does not differ much. The difference would be more visible if the inner radius was not resolved (i.e., for baselines < 40 m in the N band, or baselines < 15 m in the L' band).

5. SIMULATED OBSERVATIONS

Now that we have investigated the influence of each parameter on the nulling ratio, we will simulate observations of ζ Lep with the GENIEsim software, taking into all noise sources discussed in Absil et al. (2003), and try to retrieve the disk parameters from these observations. The observations will be done with different baselines to get as much information as possible on the cloud morphology. In these simulations, we have assumed a face-on disk, so that the baseline orientation does not matter.

5.1. Calibration of the stellar leakage

When realistic simulations are carried out, a major source of signal in the destructive output of GENIE is the *instrumental leakage*, i.e., the additional stellar signal which leaks through the null because of residual OPD, dispersion, intensity mismatches, etc. Instrumental leakage can be much larger than the signal from the dust disk, especially in the L' band. Therefore, to retrieve the actual nulling ratio from the observations, one must calibrate the raw nulling ratio with a reference star.

In the following simulations, we will assume that a calibrator star, perfectly identical to the target star except for the absence of dust, is observed before and after the target star. The observation time is set to 1000 sec, so that two calibrator measurements are separated by 1000 sec. The calibration is done as follows:

1. Compute the mean stellar leakage for the two calibrator measurements,
2. Compute analytically the physical leakage associated to the calibrator, knowing its angular diameter,
3. For the calibrator star, subtract the physical leakage from the mean leakage to retrieve the instrumental leakage,
4. Compute the estimated instrumental leakage associated to the target star from the instrumental leakage associated to the calibrator,
5. Subtract the estimated instrumental leakage from the data to retrieve the actual nulling ratio.

The most critical step in this method is the second step because the angular diameter of the calibrator has to be known with a high enough accuracy. The fourth step could also be problematic because the relationship between the instrumental leakage associated to the calibrator and to the target star is not straightforward. In practice, it turns out that the instrumental leakage does not depend much on the angular diameter of the star, which is quite comprehensible. In the following simulations, we will avoid these problems by assuming that the angular radius of the calibrator is perfectly known and that the calibrator is identical to the target star. The result will be too optimistic in the L' band where stellar leakage is critical, but not in the N band where the instrumental leakage is much smaller than the signal from the dust cloud.

5.2. Calibration of the thermal background

Besides stellar leakage, the thermal background also has an important contribution to the signal detected at the destructive output of GENIE (Absil et al., 2003). In order to remove this incoherent contribution, chopping will be used by GENIE, either with the help of the VLTI chopping mirrors for which the chopping frequency is limited to 5 Hz, or by using internal chopping (e.g. with phase modulation) at a higher frequency.

In the following simulations, we will assume that the noise due to the residual background after calibration is negligible compared to other noise sources, and especially to the shot noise associated to the background. This is the “background-limited performance” regime. The resulting signal-to-noise ratio could be somewhat optimistic, especially in the N band where the thermal background is a critical issue.

5.3. L' band simulations

Ten observations of 1000 sec in the L' band, with ten different AT baselines ranging from 8 m to 112 m, have been carried out on successive nights at the moment when ζ Lep crosses the local meridian. After calibration of the instrumental leakage, a signal-to-noise ratio of 300 on the dust emission is reached for each observation. Figure 6 shows the observed nulling ratios together with their 1-σ error bars. In the top plot of Figure 6, the physical leakage has not been removed from the data, so that the nulling ratio increases with increasing baselines as the star gets more and more resolved.

Three disk parameters (luminosity ratio, inner radius and density power-law) have been fitted to the observations. The resulting parameters are very close to the theoretical ones (cf. Table 2), with a relative error of less than 1% on their values.

Table 2. Three disk parameters have been fitted to the observed nulling ratios in the L' band (Figure 6).

	Model	Fitted	Error (1σ)
$L_{\rm dust}/L_*$	1.7e-4	1.694e-4	0.003e-4
α	0.6	0.593	0.004
$r_{\rm in}$ [AU]	0.5	0.4988	0.0006

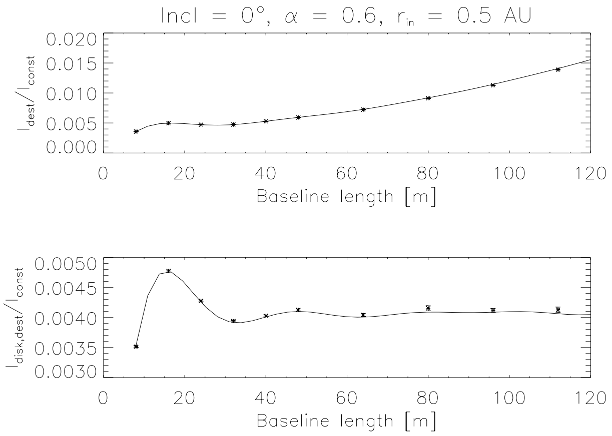

Figure 6. Solid line: theoretical nulling ratio for ζ Lep in the L' band. Data points: simulated observations of ζ Lep, with ten AT-AT baselines. Each observation of 1000 sec gives an SNR of 300 (in the whole L' band). In the bottom plot, the physical leakage from the stellar light has been removed to reveal the contribution of the disk to the nulling ratio.

5.4. N band simulations

Six observations of 1000 sec in the N band with the six different UT baselines have been carried out on successive nights at the moment when ζ Lep crosses the local meridian. Even with only 10% accuracy on the calibration of the instrumental leakage, a signal-to-noise ratio of 450 on the dust emission is reached for each observation. Figure 7 shows the observed nulling ratios together with their 1-σ error bars.

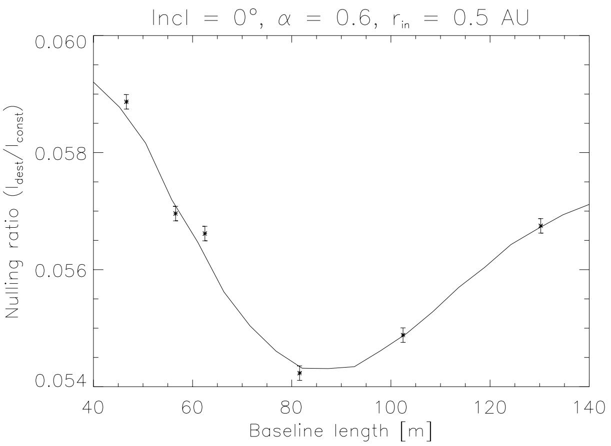

Figure 7. Solid line: theoretical nulling ratio for ζ Lep in the N band. Data points: simulated observations of ζ Lep, with the six possible UT-UT baselines. Each observation of 1000 sec gives an SNR of 450 (in the whole N band).

Three disk parameters (luminosity ratio, inner radius and density power-law) have been fitted to the observations. The resulting parameters are very close to the theoretical ones (Table 3), with a relative error of 4% or less on their values. Note that the error on the morphology parameters α and r_{in} is larger in the N band than in the L' band. This is due to the smaller range of baselines and to the lower angular resolution in the N band.

Table 3. Three disk parameters have been fitted to the observed nulling ratios in the N band (Figure 7).

	Model	Fitted	Error (1σ)
L_{dust}/L_*	1.7e-4	1.7022e-4	0.0017e-4
α	0.6	0.645	0.025
r_{in} [AU]	0.5	0.5025	0.003

Both the L' and N bands allow to retrieve the disk parameters with a very high precision. With such a precision, the possible presence of gaps due to the formation of terrestrial planets could probably be inferred. Moreover, low spectral resolution will be available on GENIE and will bring additional information, e.g. on the size of the grains.

6. SURVEY OF NEARBY STARS

6.1. Vega-type stars

Among the nearby stars that will be surveyed by GENIE are at least 40 Vega-type stars. Figure 8 gives the distances and luminosity ratios for the known Vega-type stars within 100 pc that can be observed from Cerro Paranal. This is a non-exhaustive list, and many more debris disks could be detected by GENIE and other instruments in the coming years.

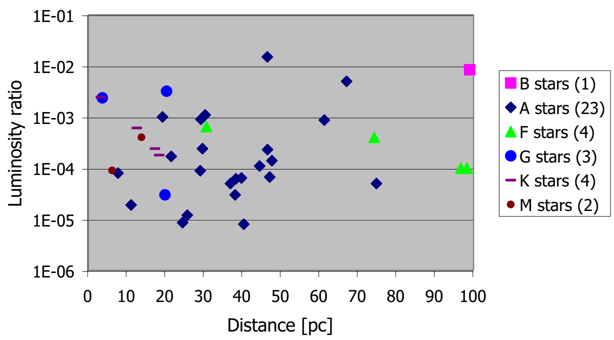

Figure 8. Known Vega-type stars within 100 pc. Debris disks are particularly frequent around A-type main sequence stars (∼10%).

6.2. Zodiacal disks

As mentioned in the introduction, the main scientific goal of the GENIE instrument is to survey the candidate DARWIN/TPF targets for the presence of circumstellar dust. Using the GENIE simulator

Table 4. Limiting number of zodis for detection of exozodiacal dust around G2V stars at different distances. The unit "zodi" corresponds to a fractional luminosity of 4×10^{-7}. The detection limit corresponds to an SNR of 3 in one hour of integration with two AT's in the L' band or two UT's in the N band.

	5 pc	10 pc	20 pc	50 pc
L' band	8	38	205	1113
N band	6	23	106	1360

and the ZODIPIC package to produce images of exozodiacal dust disks (Kuchner and Serabyn, 2001), we have computed the smallest dust fractional luminosities that can be detected with the GENIE instrument around a G2V star at different distances. In Table 4, the limiting fractional luminosity is expressed in number of "zodis", a unit corresponding to the fractional luminosity of the local zodiacal cloud $L_{\rm zodi}/L_\odot \simeq 4 \times 10^{-7}$.

The values in Table 4 are probably somewhat optimistic because:

- In the L' band, we have considered that a calibration accuracy of 0.1% can be reached for the instrumental leakage (this is our goal for an L'-band GENIE). This is particularly critical for the nearest stars, for which stellar leakage is huge. Assuming a more pessimistic calibration accuracy of 1%, the detection limit would increase to 80, 114, 340 and 1190 zodis for Sun-like stars at 5, 10, 20 and 50 pc respectively.

- In the N band, we have assumed background-limited performances. It is not clear yet whether chopping at a frequency of 5 Hz can fulfill this requirement. A measurement campaign is currently undertaken at the VLTI with the MIDI instrument to answer that question. If background fluctuations turns out to be the limiting factor, the use of internal chopping is a promising solution.

Table 4 has been obtained for a G2V star. Since the brightness of the dust disk increases with stellar effective temperature, the detection limit would be lower for A stars. For example, the detection limit for a dust disk around an A0V star at 20 pc is of only 10 zodis both in the L' and N bands. On the other hand, the detection limit would be much higher for M stars. For example, the detection limit for a dust disk around an M0V star at 5 pc is respectively of 150 zodis and 70 zodis in the L' and N bands. According to these limits, it turns out that almost all dust disks of Figure 8 can be detected with GENIE.

7. CONCLUSION

Vega-type stars have been detected so far solely by infrared photometry and/or sub-mm interferometry. Using infrared *nulling* interferometry, the starlight can be cancelled by a factor of 1000 or more so that the measurement of the disk emission can be performed with an unprecedented accuracy. This will allow to constraint unambiguously the morphology and the physics of warm dust, especially in the habitable zones of nearby main sequence stars. The ability to detect faint zodiacal disks around late-type stars will also allow GENIE to discard unsuitable targets for DARWIN/TPF.

ACKNOWLEDGMENTS

OA acknowledges the financial support of the Belgian National Fund for Scientific Research.

REFERENCES

Absil O., den Hartog R., Erd C., et al., 2003, these proceedings.

Aumann H., Gillett F., Beichman C., et al., 1984, ApJ 278, L23-L27

Backman D., Gillett F., 1987, in Cool Stars, Stellar Systems, and the Sun, ed. J. Linsky & R. Stencel (Berlin: Springer), 340.

Den Hartog R., Absil O., Kaltenegger L., et al., 2003, these proceedings.

Fajardo-Acosta S., Telesco C., Knacke R., 1998, AJ 115, 2101-2121.

Gondoin P., Absil O., Fridlund M., et al., 2003, Proc. SPIE 4838, 700-711.

Kaltenegger L., Absil O., Eiroa C., et al., 2003, these proceedings.

Kuchner M., Serabyn E., accepted for publication in ApJ, 2001.